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NATURE OF THE ASTHENOSPHERE

BY REGINALD A. DALY

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ABSTRACT

From the geophysical and physical laboratories at Harvard University have recently come data bearing on the effect of rising temperature on the compressibility of liquids, glasses, and crystalline solids. These new data have compelled the author of the following article to revise an earth-model which, in 1942, he derived from some general assumptions as to the condition of the globe at its beginning. According to the 1942 model the asthenosphere is pictured as chiefly peridotitic and wholly vitreous; according to the revised model the deeper and greater part of the thick, weak earth-shell is pictured as peridotitic and in the form of a two-phase mixture of dominant crystals and subordinate glass or, possibly, a gaseous solution in the critical state. The revised model seems to suggest good explanation for the weakness, high rigidity, and great viscosity of, and high velocities of seismic waves in, the outer half of the earth's silicate mantle.

During the revision there was the incidental discovery of a method of finding, to a close approximation, the compressibility of a crystalline rock from the norm corresponding to the chemical analysis of the rock, and this at pressures ranging from 1 bar to 10,000 bars; with a somewhat greater chance of error the method can be usefully applied up to 30,000 bars.

INTRODUCTORY STATEMENT

In 1942 the writer sent to press a paper (Daly, 1943), describing an earth-model unlike any of those which had been offered by others. That paper was published in the hope that geophysicists might criticize another bold venture into the "fan-

tastically difficult" problem of the earth's interior and in so doing improve on the necessarily deductive scheme. To put the speculation in debatable form, eight earth-shells and a central core were assigned definite compositions, thicknesses, and temperatures. The chain of deductions was based on a fundamental assumption: that the earth was initially a gas-ball, composed largely of hydrogen and other volatile gases holding in mutual solution enough material like that of the average meteorite to make the existing planet—the residuum after the hot gas-ball lost most of its original mass by molecular flight into space. Early gravitative differentiation of the iron core from the overlying silicate mantle was assumed. It was suggested that at present the silicate mantle between the approximate depths of 450 and 2900 kilometers is crystallized, truly solid, and that the layer between the 450-kilometer level and the average depth of 70 kilometers is vitreous and somewhat hydrous.

The vitreous substratum of the 1942 earth-model was described as largely of peridotitic composition, basaltic glass being only a few kilometers in thickness and perhaps discontinuous around the globe. It was indicated, however, that in earlier geological periods the crust was thinner and that the basaltic substratum may have been considerably thicker than now, as well as world-circling. With this fundamental, century-old hypothesis the writer still finds the best basis for understanding igneous action, both volcanic and plutonic. A vitreous state for the dominantly peridotitic layer seemed, in its turn, to provide an asthenosphere with sufficient weakness to account for proved isostatic adjustment.

The idea of the thick layer of vitreous peridotite was risked in the 1942 writing despite two more or less manifest difficulties in the way of its acceptability: In the first place, it was uncertain that the high pressure on the layer could give it a viscosity to match the proved leisureliness of isostatic adjustment, to permit a mean rigidity for the earth as indicated by the amount of yielding to lunar-solar stresses, and to account for seismic foci located well within the upper and lower limits of the layer. And, secondly, it was realized that geophysicists doubt that such a vitreous layer could have the compressibility and effective rigidity needed to explain the velocities of earthquake waves through it.

The first uncertainty has not been removed by direct experiments on molten peridotite at any all-sided pressure, and there appears to be no theoretical basis on which to estimate even roughly the effect of pressure on the viscosity of that liquid when subjected to small shearing-stress for short periods. Final judgment in the matter of viscosity must, apparently, await new data from the high-pressure laboratory.

The situation is now seen to be different in the case of the second uncertainty mentioned. In 1942 the writer had overlooked the significance of recent high-pressure experiments by Birch and Bancroft and by Bridgman. Birch and Bancroft (1942, p. 487) found an indirect way of estimating the effect of increase of temperature on the compressibility of diabase-glass at atmospheric pressure. At this low pressure the compressibility rises at an accelerating rate. Experiments by Birch and his assistants had shown the same to be true of holocrystalline rocks, for which, however, the acceleration is lessened by increase of pressure. This deduction from the rather meager experimental data on rock materials matches that derived from Bridgman's studies of highly compressible liquids and their pressure-crystallized equivalents. Using the results of these masters in high-pressure research, the pres-

ent writer, in 1945, came to doubt that the asthenosphere of his 1942 earth-model—between the depths of 70 and 450 kilometers—is wholly vitreous. A manuscript detailing the argument on which this doubt is based was submitted for criticism to Professor Birch after his release from war service. He has made clear that much experimental work in the high-pressure laboratory is needed before there can be certainty in the matter, but agrees that such relevant facts as we have do not favor the 1942 picture of the asthenosphere. The following pages summarize the destructive argument and then present the less vulnerable hypothesis that all but a small fraction of the asthenosphere is peridotite in the form of a two-phase mixture.

Several steps in the final elaboration of the two-phase hypothesis have also been debated with Professor Birch. He drew upon his unrivalled experience with the experimental study of rocks and glasses at high temperature as well as high pressure to give unstinted advice. For all this generous help the writer wishes to record grateful thanks, while just as emphatically he begs the reader not to hold Professor Birch responsible for errors to be discovered in the text or general reasoning of this article, or for the ambition to plunge into the unknown so far beyond the scope of controlled data. Nevertheless, Professor Birch has gone so far as to say that the new speculation may help to show where further experimental work on rock materials is urgently needed.

HYPOTHESIS OF A VITREOUS STATE AT THE DEPTH OF 100 KILOMETERS IN THE EARTH

A SPECIFIC CRITERION

The immediate, specific problem is, then, to answer the question whether the thick asthenosphere of the 1942 earth-model would give the known velocities of seismic waves at the corresponding range of depths in the earth. Between the depths of about 50 and 100 kilometers neither the velocities nor Poisson's ratio have been determined by the seismologists. At the 100-kilometer level the velocity (V_p) of the longitudinal or compressional wave is now generally taken to be close to 8.0 kilometers per second, with Poisson's ratio at 0.27. Analysis of conditions at this level seems able to declare whether peridotitic material—much the most probable kind—between the depths of 70 and 450 kilometers can be vitreous.

The relations to be considered are given by the following equation:

$$V_p = 13.13/\sqrt{10^6\beta \cdot \rho}$$

where β is the cubic compressibility expressed in terms of the reciprocal bar, ρ is the density, and V_p is in kilometers per second.[1]

Before the testing equation can be used, adequate estimates of β and ρ for vitreous peridotite at the 100-kilometer level must be in hand. Both terms are functions of pressure and temperature, neither of which is known with exactitude. In the 1942 earth-model values for that level were assumed at 30,000 bars and 1500°C. These estimates are retained for present use; departures from the actual truth are not likely to affect seriously the value of the test to be applied.

[1] This convenient form of statement is quoted from Adams and Williamson (1923, p. 526).

CHEMICAL COMPOSITION

The density and elasticity of the deep material are functions of the chemical composition. The recognized types of peridotite have wide ranges in oxide percentages, and no single analysis can be selected as representing any of the types to general satisfaction. It seems best, therefore, to use world averages. Such averages have been computed by Daly (1933, p. 20) for dunite, harzburgite, lherzolite, and wehrlite, and, with their norms, are entered in Table 1. There also will be found an average for the composition of 20 achondritic meteorites (Washington, 1925, p. 357) and an average for 63 stony meteorites (Merrill, 1930, p. 47).

It is uncertain how much of the water in the original analyses is due to alteration by weathering; hence in the interest of fruitful comparisons all averages are stated on a water-free basis. All were reduced to totals of 100.00 per cent. Before such reductions some quite minor constituents were omitted, but for our present purpose the omissions have no practical importance.

DENSITY

The densities of the holocrystalline materials at room temperature (20°) and 1 bar are entered in column 1 of Table 3. They were computed by the method of Iddings (1920, p. 363), shown to be remarkably accurate for pore-free rocks. (*See* Daly, 1935, p. 657.) The corresponding densities at 1500° and 1 bar and at 1500° and 30,000 bars were computed with the data of columns 1 and 2 of Table 2. The percentages for thermal expansion (column 1) were found by weighting the measured expansions of the norm minerals. The percentages for contraction by pressure were found by similar integration of the pressure effects; net results are shown in column 2, Table 2.

Direct and reliable measurements of the density of a vitreous peridotite at any temperature or pressure are not available, but the densities of our glasses can be estimated with a fair degree of closeness. It is known that pore-free diabase loses between 6 and 7 per cent of its density on conversion to glass at 20°. Pyroxene loses about twice as much in percentage. According to a personal communication from Professor N. L. Bowen olivine loses about 5 per cent on melting. It appears, therefore, that the respective changes of density with melting at 1500° and 30,000 bars are approximately those entered in column 3 of Table 2.

With the data of that table the densities of our peridotitic types in the crystalline state under different conditions of temperature and pressure, and the density of the same materials when vitreous at 1500° and 30,000 bars, have been computed. The results are stated in columns 1 to 4 of Table 3, where, for comparison, the values are given for a rock entirely composed of olivine. Any errors occurring in the table are believed to be too small to invalidate the general argument to be presented.

COMPRESSIBILITY

Much greater errors are possible in the attempts to learn the corresponding compressibilities. No crystalline peridotite has yet yielded direct measurements under anything like the conditions of the 100-kilometer level in the earth. Moreover, it will be long before an adequate specimen of a peridotite-glass has been prepared for

TABLE 1.—*Average compositions, norms, and densities*

	1	2	3	4	5	6
	Dunite	Harzburgite	Lherzolite	Wehrlite	Acondritic meteorite	Stony meteorite
SiO_2	41.69	42.81	44.44	46.51	49.25	43.35
TiO_2	.02	.12	.10	.66	—	.18
Al_2O_3	.89	1.31	4.87	5.93	6.19	3.23
Fe_2O_3	2.93	2.66	2.22	3.54	—	1.04
FeO	5.70	6.48	6.41	9.84	15.98	15.25
MnO	.16	.19	.19	.27	.23	.26
MgO	47.70	44.61	37.21	23.61	18.27	26.73
CaO	.72	1.36	3.61	7.72	7.17	2.13
Na_2O	.10	.29	.64	1.17	.67	.93
K_2O	.04	.13	.21	.59	.27	.18
P_2O_5	—	.04	.10	.16	—	.38
Cr_2O_3	—	—	—	—	.46	.45
S	.05	—	—	—	.55	2.14
Fe (for FeS)	—	—	—	—	.96	3.75
	100.00	100.00	100.00	100.00	100.00	100.00
Norms						
Orthoclase	.22	.55	1.11	3.36	1.65	1.11
Albite	1.06	2.62	5.26	10.03	5.73	7.88
Anorthite	1.65	1.94	10.04	9.24	13.00	3.90
Diopside	1.31	3.49	5.48	22.70	18.27	3.37
Hypersthene	5.83	8.76	10.50	11.72	40.42	28.24
Olivine	85.61	78.26	63.90	36.27	18.77	46.29
Magnetite	4.20	4.14	3.25	5.14	—	1.39
Ilmenite	.03	.15	.15	1.23	—	.31
Apatite	.09	.09	.31	.31	—	.93
Chromite	—	—	—	—	.67	.68
Troilite	—	—	—	—	1.49	5.90
	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 2.—*Assumed changes of density of crystalline peridotites with heating, and with change to the glassy state*

In percentages.

	1	2	3
	Decrease by rise of temperature, 20° to 1500°, 1 bar	Increased by rise of pressure to 30,000 bars	Decreased by change of state at 1500° and 30,000 bars
Olivine-rock	5	2.3	5
Dunite	4.5	2.5	6
Harzburgite	4.5	2.5	6
Lherzolite	4	2.5	6
Wehrlite	3	2.8	6
Achondritic meteorite	3	2.7	6
Stony meteorite	3.5	2.5	6

such study in the high-pressure laboratory. At present relevant data can be found only in an indirect way, a method which, however, in spite of its being charged with uncertain factors, does seem competent to help in a wise decision as to the state of the asthenosphere.

TABLE 3.—*Densities and compressibilities of peridotitic materials*

	Density				Compressibility (× 10^6)			
	1	2	3	4	5	6	7	8
State	cryst.	cryst.	cryst.	glass	cryst.	glass	glass	glass
Temperature	20°	1500°	1500°	1500°	20°	20°	20°	1500°
Pressure (bars)	1	1	30,000	30,000	1	1	30,000	30,000
Olivine-rock	3.35	3.18	3.26	3.05	.85	.935	.888	.977
Dunite	3.37	3.22	3.30	3.13	.89	.978	.929	1.022
Harzburgite	3.35	3.20	3.28	3.11	1.00	1.100	1.045	1.149
Lherzolite	3.26	3.12	3.21	3.02	1.01	1.111	1.055	1.161
Wehrlite	3.25	3.15	3.25	3.05	1.11	1.222	1.161	1.277
Achondritic meteorite	3.25	3.15	3.25	3.05	1.10	1.220	1.159	1.275
Stony meteorite	3.34	3.20	3.30	3.15	1.09	1.200	1.140	1.254

The proposed indirect method of attack involves the taking of four successive steps, estimating: (1) the compressibility of the holocrystalline material at 20° and 1 bar; (2) the change in its value when the material becomes vitreous at 20° and 1 bar; (3) the effect of raising the pressure to 30,000 bars; and (4) the counteracting effect of heating to 1500°. At each step care is taken to select those estimates which, while not unreasonable, ensure minimum compressibility and therefore maximum wave-velocity in each glass when at 1500° and 30,000 bars.

When that method is applied, it is seen that none of the peridotite-glasses is likely to give a seismic wave traversing it as high a velocity as that determined for the 100-kilometer level by the seismologists. A better correlation will be made, later on in this paper, when the assumption is made that the material at the level described is crystallized except for a few per cent of its volume.

(1) The compressibility of any of our six holocrystalline (water-free) peridotites at 20° and high pressure can be rather closely inferred from the norm given in Table 1. Adams and Williamson (1923, p. 517) showed that the mode can be similarly used in calculating the compressibility of any of the important types of igneous rocks, wholly crystallized. Using the data of column 1, Table 4, the writer has calculated from their norm (standard) minerals the compressibility of Sudbury diabase, Whin Sill diabase, Palisades diabase, and Maryland diabase; he finds the mean ratio of such "norm" compressibility to measured compressibility at 1 bar to be 1.0075, as against a ratio of 0.9522 for mode compressibility to measured compressibility. The modes used are those actually published. The respective mean ratios for two granites are 0.9925 and 0.9615. The sanction for preferring the norm instead of the mode for use in such calculations is largely due to the difficulty of accurate measurement of the volumes of mode minerals. Incidentally, it may be noted that, if garnet were an

important mineral in our six peridotites, calculation of compressibility from the norm minerals would be in decided error, but that objection to their use is nullified by the fact that essential garnet is generally absent from the peridotites under discussion, whether terrestrial or meteoritic.

TABLE 4.—*Data concerning norm minerals at 20°C*

	Compressibility × 10^6				Density at 1 Bar	Density at 30,000 Bars	Specific Volume at 30,000 Bars
	1	2	3	4	5	6	7
	At 1 bar	At 10,000 bars	At 20,000 bars	At 30,000 bars			
Quartz	2.70	2.20	1.77	1.40	2.65	2.80	.357
Orthoclase	2.12	1.85	1.59	1.34	2.54	2.67	.375
Albite	1.90	1.70	1.55	1.42	2.61	2.74	.365
Anorthite	1.09	1.04	1.00	.98	2.77	2.85	.351
Diopside	1.07	.95	.86	.79	3.28	3.37	.296
Hypersthene	1.04	.97	.90	.84	3.40	3.50	.286
Olivine	.85	.82	.79	.76	3.30	3.38	.293
Magnetite	.55	.51	.49+	.49−	5.17	5.24	.191
Ilmenite	.56	.52	.50+	.50−	4.75	4.82	.208
Chromite	.6 (?)	—	—	.58 (?)	4.40	4.47	.224
Troilite	1.60	—	—	1.25	4.80	4.87	.197
Apatite	1.09	1.00	.94	.90	3.20	3.29	.304

For lack of actual measurements the compressibilities of chromite and troilite had to be guesses. Because of the small proportions of these compounds, which appear in only two of the materials, the errors due to faulty guessing are unimportant. All other values in columns 1 and 2 of Table 4 have been carefully determined in high-pressure laboratories. The values given in columns 3 and 4 (the latter to be of special interest later on) were derived by extrapolation along the pressure-compressibility curves developed during those series of actual measurements. Such violent extrapolation may somewhat exaggerate the pressure effect, but error from this cause would probably, for all the glasses, make calculated wave-velocities too high and would not vitiate the general conclusion to be reached in making comparison with seismologically-measured velocities.

Columns 5, 6, and 7 of Table 4 carry the data needed for calculating the densities and compressibilities of the crystallized peridotites at 30,000 bars, all at 20°.

The compressibility of each glass at 1500° and 30,000 bars was estimated by making allowance for change of state and also for the effect of the high temperature. Neither adjustment can now be made except in a roundabout way and must be only approximate. Nevertheless, it is believed that recognition of limits for possible estimates of the two influences permits solution of our present problem. It is only necessary to choose: (a) a minimum possible value for the compressibility of each glass at 20° and 1 bar, and (b) a minimum increase of compressibility when the given glass is exposed to the temperature of 1500° and pressure of 30,000 bars.

(2) The first-mentioned of these two adjustments has been made by using results of studies on obsidian and diabase-glass. Table 5 gives the norm (crystalline-state) and directly measured compressibilities of obsidian and diabase-glass, at 20° and 1 bar.

In average the excesses of compressibility for glass over that for the crystalline

TABLE 5.—*Compressibilities of obsidian and diabase-glass at 20° and 1 bar*

($\times 10^6$)

	Norm	Measured
Lipari obsidian	2.13	2.84
Yellowstone Park obsidian	2.21	2.85
Ascension Island obsidian	2.09	2.90
Averages	2.14	2.86
Westfield diabase-glass	1.39	1.53
Vinal Haven diabase-glass	1.27	1.50
Averages	1.33	1.52

equivalent are: for obsidian 33 per cent, and for diabase 14 per cent. The corresponding percentage for the still more basic peridotite is probably a little less than 14 per cent; for safety in drawing final conclusions the excess for each of our six peridotites will be taken as low as 10 per cent. Column 6 of Table 3 states the corresponding figures for the compressibilities, as well as of olivine-rock glass, at 20° and 1 bar.

(3) We now take the third step. Adams and Williamson (1923, p. 507) proved that there is remarkably little change in the compressibility of obsidian when all-sided pressure upon it is raised from 1 bar to 12,000 bars. Adams and Gibson (1926, p. 279) had a similar experience with Kilauea tachylite, the top pressure being 10,000 bars. So it was too with Birch and Law (1935, p. 1245) in the case of diabase-glass, for which the increase of compressibility with rise of pressure by 17,000 bars has been estimated by Birch and Bancroft (1942, p. 486) at less than 1 per cent. Bridgman's apparatus, designed for measurements up to 50,000 bars, gave its most trustworthy results at pressures above 10,000 bars; with it he found no appreciable change in the compressibility of diabase-glass when the pressure was raised from 20,000 bars to 45,000 bars. (*See* Handbook of Physical Constants, 1942, p. 51.) Reviewing all the evidence, Birch and Bancroft (1942, p. 486) concluded that for rock-glasses the effect of even great increase of pressure on compressibility is "very small". However, again for safety's sake, we shall assume that in the case of glassy peridotite a rise of pressure from 1 bar to 30,000 bars decreases the compressibility as much as 5 per cent. Using this percentage the compressibilities of our six peridotites and of olivine-rock at 20° and 30,000 bars are found to have the values stated in column 7 of Table 3.

(4) Obtaining even a rough idea of the temperature coefficient for a peridotite-

glass, in the absence of direct measurements, is possible only after a daring use of analogies derived from experiments on diabase-glass and on alcohols and other liquids.

By finding the natural frequencies of free vibration of a cylinder of Westfield diabase-glass, the Young's modulus of the glass at 1 bar was determined by Birch and Bancroft (1942, p. 459) at 100-degree intervals from 0° to 600°. From the changes of the modulus thus found the corresponding changes of compressibility can be inferred, as those authors point out. The relative amounts of the latter changes are given in Table 6.

TABLE 6.—*Relative compressibilities of diabase-glass at 1 bar and at seven temperatures*

Temperature	Ratios for Compressibility	Differences
0°	1.0000	
		.0081
100	1.0081	
		.0093
200	1.0174	
		.0104
300	1.0278	
		.0130
400	1.0408	
		.0172
500	1.0580	
		.0241
600	1.0821	

The column of "differences" in the table shows that the rate of increase of compressibility with rise of temperature is notably accelerated. Extrapolating from the curve illustrating this fact quantitatively, the compressibility at 1500° at 1 bar comes out at something like 70 per cent higher than that at 20°.

Professor Birch reports that because of a technical difficulty the sonic method has not yet permitted direct measurement of the change of compressibility of a rock-glass (rigid or molten) with simultaneous rise of temperature and pressure. The best suggestions bearing on that question seem to come from analogies derived from study of much more compressible substances. It goes without saying that we may expect no more than discovery of the probable trends in the case of the much less compressible glasses. Nevertheless, until more direct high-pressure experiments have been made on these, it is worth while to accept analogy as a guide to thought.

Bridgman (1913) made the relevant investigation in the case of the highly compressible liquids. From his tables for seven liquids the percentage increase of compressibility caused by heating from 20° to 80°C. at 500 bars and at 11,000 bars have been computed, with the results shown in Table 7. In average the percentage for 500 bars is 8 times that for 11,000 bars.

Bridgman (1942) made a similar study, changing the temperature from 25° to 175° and running the pressure up to 50,000 bars. From these newer tables the increase of compressibility with rise of 50° in temperature. at 7500 bars, has been found,

for 11 liquids, to be accelerated at a nearly constant average rate of 8 per cent (8.5 per cent between 25° and 75°; 7.8 per cent between 75° and 125°; and 7.8 per cent between 125° and 175°).

Six liquids—ethyl alcohol, n-propyl alcohol, i-propyl alcohol, n-amyl alcohol, ethyl bromide, and ethyl acetate—were exposed to pressures at 10,000, 20,000, 30,000, and 40,000 bars. The changes of compressibility when the temperature in each case was raised from 125° to 175° were in percentages somewhat erratic. The reason for this may perhaps in part be ascribed to errors inevitably connected with the exceedingly delicate conditions of measurement, in other part to the rounding of figures designating changes of volume. If there be no systematic error it would be clear that there is less and less acceleration of the temperature coefficient as the pressure rises. The computed averages for the rates of increase of compressibility due to the 50-degree heating are as follows: at 10,000 bars +5.2 per cent; at 20,000 bars +2.4 per cent; at 30,000 bars −0.1 (negative) per cent; at 40,000 bars −0.03 (negative) per cent.

Similar averages were struck for the four alcohols (all escaping pressure-crystallization) with the temperature range from 75° to 175°. The percentages at the four pressures are respectively 10.4, 8.5, 5.2, and 1.2, each having the positive sign.

Taken at their face value, Bridgman's results indicate the likelihood that also in

TABLE 7.—*Percentage increase of compressibility of liquids when heated from 20° to 80° C., at two different pressures**

	At 500 Kg./Cm.²	At 11,000 Kg./Cm.²
Methyl alcohol	29	1.7
Ethyl alcohol	24	2.6
Propyl alcohol	29	8.9
Isobutyl alcohol	27	3.6
Amyl alcohol	26	2.4
Phosphorus trichloride	29	5.3
Ethyl iodide	21	1.0
Averages	26.4	3.6

* In this table the unit of pressure is that used by Bridgman, but for convenience in printing the unit employed in the present paper is the bar; no significant error in stating the results of computation is caused thereby.

the case of vitreous peridotite the rate of increase of compressibility with rise of temperature, even at a pressure as high as 30,000 bars, has a slow increase; in fact, that a molten peridotite at the depth of 100 kilometers in the earth is at least 10 per cent more compressible than the same glass at 20° and 1 bar. A better estimate may well be 15 per cent or somewhat more, but for safety in applying our test the lower percentage will be assumed. On this basis the compressibilities of the six peridotites in the vitreous state at the 100-kilometer level have been calculated, with the results shown in column 8 of Table 3. Column 4 of the same table gives the corresponding densities.

WAVE-VELOCITIES

Table 8 gives densities and compressibilities of, and related wave-velocities in, the peridotitic glasses under the assumed conditions of the 100-kilometer level.

As already remarked, the densities cannot be far wrong, and the compressibilities are probably lower than those to be found if our glasses, at 1500° and 30,000 bars,

TABLE 8.—*Computed densities, compressibilities, and maximum wave-velocities in glasses at 1500° and 30,000 bars*

	Density	Compressibility ($\times 10^6$)	V_p Km(./Sec.)
Olivine-rock	3.05	.977	7.60
Dunite	3.13	1.022	7.34
Harzburgite	3.11	1.149	6.95
Lherzolite	3.02	1.161	7.00
Wehrlite	3.05	1.277	6.64
Achondritic meteorite	3.05	1.275	6.65
Stony meteorite	3.15	1.254	6.61

TABLE 9.—*Velocities of seismic waves (V_p and V_s) at the depths indicated (km./sec.)*

Depth (Km.)	V_p	V_s
100	7.95	4.45
200	8.26	4.60
300	8.59	4.77
400	8.93	4.94
500	9.66	5.32

could be directly tested in the laboratory. The tabulated velocities are almost certainly too high by at least 2 or 3 per cent. Even as they stand the values in the third column of the table are decidedly lower than those found by Jeffreys and Gutenberg (*see* Handbook of Physical Constants, 1942, p. 101)—namely 7.95 and 8.0 kilometers per second—for the depth of 100 kilometers in the earth.

In his exceptionally thorough analysis of the seismological data Jeffreys deduced velocities for the longitudinal wave (V_p) and transverse wave (V_s) at depths reaching 500 kilometers in the earth, with amounts shown in Table 9. (*See* Daly, 1943, p. 431, with reference.) Both velocities rise with increase of depth at rates chiefly determined by decrease of compressibility with the increase of depth, and this down to and including the 400-kilometer level. Between that level and one 300 kilometers higher the material seems to be nearly homogeneous, though probably with a slight increase of chemically-determined density as the depth grows greater.

The relatively big jumps in the velocities between the 400-kilometer and 500-kilometer levels were in 1942 (Daly, 1943, p. 433) interpreted as due mainly to change from glass to crystalline rock, of similar composition, below. If, as the general argument of the present paper suggests, the material at and below the 100-kilometer level is not vitreous, some other explanation of the discontinuity mentioned must be sought. (*See below.*)

CONCLUSION

The great thickness of the nearly homogeneous layer makes it hard to believe that its high wave-velocities indicate a glass made of pure olivine. As seen from Table 8 even this material is not "speedy" enough to match the seismological datum. No meteorite of pure olivine is known, and it is highly doubtful that so thick a layer of pure olivine could have been formed during the differentiation of the relatively thin, more superficial layers of granite, intermediate rock, and gabbroid or eclogitic rock. Correlation of any other of the velocities stated in Table 8 with the seismically-determined velocity at the 100-kilometer level is still more difficult. Here at last, even after attaining a lively sense of many uncertainities in our argument, we seem compelled to discount the idea that the asthenosphere is a vitreous peridotite. It has been made quite clear by Birch and Bancroft (1942, p. 487) that vitreous basalt is still less likely to dominate in the weak earth-shell.

HYPOTHESIS OF A HOLOCRYSTALLINE ASTHENOSPHERE

As we turn attention to the reasons for the alternative suggestion—that the weak shell of the earth is a two-phase mixture—it is expedient to inquire as to what wave-velocity (V_p) should be expected at the 100-kilometer level if the material there were a completely crystallized equivalent of one of our six peridotites. As before a temperature of 1500° and a pressure of 30,000 bars will be assumed. The corresponding densities are given in column 3 of Table 3, where column 5 gives the computed compressibilities of the same materials when at 20° and 1 bar. These values are not likely to be far out of the way. The influence of the high pressure on the compressibility can be fairly well estimated, but that of the high temperature is more elusive. As in the case of vitreous peridotite, it will be long before the relation between pressure and the temperature coefficient of compressibility can be fixed by laboratory tests on white-hot, crystalline peridotite. Here, too, however, it seems reasonable to guide thought by using analogies derived from experimental studies on other kinds of material.

With the sonic method Birch and Bancroft (1940, p. 760) found the temperature coefficients of V_s (velocity of the transverse wave) in anorthosite at 4300 bars to be -45×10^{-6} and at 8600 bars -35×10^{-6}; hence the addition of 4300 bars reduced the temperature coefficient for rigidity by about 40 per cent. The range of temperature was from 30° to 150°. Under the same experimental conditions the temperature coefficient for rigidity of hypersthenite was reduced about 45 per cent. These findings suggest that a pressure of 30,000 bars on crystalline peridotite might possibly in the same temperature range reduce the coefficient nearly to zero. A similar relation may be expected in the case of compressibility.

That expectation seems strengthened by Bridgman's (1942) direct measurements of compressibility for solids which were pressure-crystallized from alcohols and other liquids and exposed to all-sided pressures greatly exceeding the respective, already elevated pressures of crystallization. According to his tabulated results the increase of pressure diminishes the temperature coefficient at a notable rate and even reverses its (initially positive) sign. Illustrations of both of these effects are to be found in

Table 10, which gives the percentage changes of compressibility due to rise of temperature by 50°, at pressures ranging between 20,000 and 45,000 bars. In most cases the coefficient at the higher pressures is actually negative. Of course it is conceivable that the change of sign is only apparent and perhaps caused by some undetected,

TABLE 10.—*Percentages of increase (+) or decrease (−) of compressibility of solids (pressure-crystallized phases) at high pressures and with heating by 50°*

	Pressure (Bars)	Rise of Temperature	
	1	2	3
		25° to 75°	75° to 125°
n-Butyl alcohol	20,000	+13.5	—
	45,000	−5.4	—
Ethyl bromide	35,000	+4.0	—
	45,000	−5.4	—
n-Propyl bromide	30,000	+8.7	—
	45,000	−7.0	—
Ethyl acetate	30,000	+3.5	—
	45,000	−17.0	—
n-Amyl ether	30,000	−6.8	—
	45,000	−0.2	—
Chloroform	20,000	+5.2	+7.5
	40,000	−5.2	−10.8
Carbon bisulphide	30,000	−0.2	+18.2
	40,000	+4.5	−13.0
Methylene chloride	25,000	+15.0	—
	40,000	−10.8	−6.0
Cyclohexane	20,000	+8.1	+12.5
	40,000	−0.2	−10.9
Methyl cyclohexane	25,000	+3.3	—
	45,000	+6.2	—

systematic error in the technique of measurement, which we have seen to be perforce charged with difficulties. Yet, as they stand, Bridgman's tables show the same general pressure-coefficient trend as that disclosed when Birch and Bancroft subjected anorthosite and hypersthenite to test by the indirect, quite different, sonic method of measurement.

In the light of these various analogies it seems reasonable to suppose that at 1500° and 30,000 bars crystalline peridotite would be no more than 5 to 15 per cent more compressible than the same rock is at 20° and 30,000 bars, if, indeed, there is any important difference whatever. Assuming the percentages to be 0, 5, 10, and 15, the compressibilities of our six peridotites under the conditions of the 100-kilometer level have been computed. The respective results appear in columns 1 to 4 of Table 11, where column 5 repeats the figures for density.

With those data, Poisson's ratio being held at 0.27, the respective wave-velocities (V_p) have been calculated and entered in columns 1 to 4 of Table 12, where column 5 repeats the velocities of Table 8, referring to our peridotitic types in the vitreous

state, and column 6 states more probable maxima for these glasses, also supposed to be under the conditions of the 100-kilometer level.

All estimates of velocity would have to be slightly higher if formal account were taken of the fact that the compressibility of each norm mineral is that found by the

TABLE 11.—*Compressibilities of holocrystalline peridotites at 1500° and 30,000 bars* ($\times 10^6$), *with densities*

	1	2	3	4	5
Olivine-rock	.76	.798	.836	.873	3.26
Dunite	.80	.840	.880	.920	3.30
Harzburgite	.85	.892	.935	.977	3.28
Lherzolite	.86	.903	.946	.989	3.21
Wehrlite	.90	.945	.990	1.035	3.25
Achondritic meteorite	.89	.940	.994	1.029	3.25
Stony meteorite	.89	.934	.979	1.023	3.36

TABLE 12.—*Variation of* V_p *in holocrystalline peridotites at 1500° and 30,000 bars, according to four different assumptions as to the temperature effect on compressibility (columns 1 to 4)*

Columns 5 and 6 give alternatively suggested values for V_p in the vitreous equivalents, V_p in km./sec.

	1	2	3	4	5	6
Ratios of compressibilities assumed	1.00	1.05	1.10	1.15	—	—
Olivine-rock	8.34	8.15	7.95	7.79	7.60	7.42
Dunite	8.08	7.88	7.70	7.54	7.34	7.16
Harzburgite	7.86	7.66	7.50	7.34	6.95	6.77
Lherzolite	7.90	7.71	7.53	7.37	7.00	6.82
Wehrlite	7.68	7.50	7.32	7.16	6.64	6.46
Achondritic meteorite	7.72	7.51	7.33	7.17	6.65	6.48
Stony meteorite	7.66	7.48	7.30	7.14	6.61	6.44

high-pressure apparatus (isothermal, not adiabatic, conditions), while what is needed is the higher "dynamically-measured" value. And, in the case of each crystallized peridotite, another correction in the same sense would be necessary if we make the reasonable supposition that the constituent, highly heated crystals at the 30,000-bar pressure lack any of the porosity represented by the cleavage-cracks of the laboratory specimens. Partial closing of these cracks as the pressure rises to 10,000 or 12,000 bars, the temperature remaining low, adds a little to the compressibility which would be found if there were no cracks. Under the conditions of actual measurements in the laboratory, complete closure seems never attained. At 1000° or 1500° and 20,000 or 30,000 bars, on the other hand, one would expect cleavages to be merely potential and not "realized" and therefore causing no apparent increase in the true compressibility.

Possibly both corrections together would diminish the seismically-effective compressibilities of olivine and pyroxene below the values shown in columns 1 and 2 of Table 4 by 2 or 3 per cent.

The seismically-determined V_p for the 100-kilometer level, namely about 8.0 kilometers per second, is best matched in columns 1 to 4 of Table 12 by dunite, harzburgite, and lherzolite.

Especially important is the question whether a high degree of crystallinity for the asthenosphere agrees with the property from which was derived the name of this earth-shell—its great weakness.

HYPOTHESIS OF A TWO-PHASE ASTHENOSPHERE

WEAKNESS

If the rock at, and for a long distance below, the 100-kilometer level were composed of nothing but crystallized olivine at or near its melting-point, one could imagine the strength of this deep-lying material to approach zero. But, as we have seen, the differentiation of the earth-shells, however it was done, would hardly be likely to produce a layer of pure olivine several hundreds of kilometers in thickness. We have also learned from Table 12 that the wave-velocities between the 100-kilometer and 400-kilometer levels are probably too low for pure olivine rock at these depths. We recall, too, that no meteorite composed of pure olivine has yet been described. Both on *a priori* grounds and because of the seismological data it seems necessary to postulate a multi-component peridotite for the shell. Such a rock has a relatively long temperature-interval of crystallization. For example, from a harzburgite or lherzolite melt olivine, pyroxene, and a moderate amount of highly basic plagioclase are exsolved at high temperature. After a fall of several hundreds of degrees some of the remaining liquid, probably of basaltic composition, as Bowen (1928, p. 315) has suggested, begins to crystallize. With still further cooling a hydrous solution above its critical temperature represents the residual fluid. For this interstitial fluid a temperature of something like 600° would be appropriate. Hence, no matter what may now be the temperature at the 100-kilometer level—between the limits 1100° to 1500°—the deep layer in question, if it is being slowly cooled, should include a multitude of fluid cells. Is it not possible, therefore, that such interstitial fluids serve as lubricants in a largely crystallized peridotite? Is it not natural to attribute the weakness of the asthenosphere to lubrication of the kind?

That solution to our present problem cannot, however, satisfy until two obvious questions have been answered.

First, can there be valid correlation with the seismological data? The wave-velocity in the imagined two-phase asthenosphere would be lower than in an otherwise equivalent holocrystalline asthenosphere. If, however, at the present time the interstitial fluid cells constitute only a few per cent of the volume of any of our peridotites, V_p would be only a small fraction lower than the corresponding velocity listed in any of the columns 1 to 4 in Table 12. When it is considered: (1) that the latter values are only approximate and respectively perhaps too low, and (2) that the seismologically measured wave-velocities in depth are themselves liable to corrections, especially after the true velocities above the 100-kilometer level are more accurately determined, there seems to be no antecedent objection to the proposed explanation of asthenospheric weakness.

The second question is: can a two-phase condition at depth persist to the present day after the lapse of many millions of years since the outer part of the earth became largely crystallized? When, early in the history of the globe, the pressure-crystallization of the lower two-thirds of the silicate mantle occurred (according to a general evolutionary hypothesis tentatively held), the liquid cells were there large and made up initially a large fraction of the total volume of the crystallizing meteoritic material. The dead weight of the denser crystal-mesh and the persistent tidal stressing of the deep material would be expected to have squeezed up, toward the surface, a large volume of basaltic material—a corollary which in principle recalls Bowen's (1928, p. 315) hypothesis for the origin of basaltic magma. (*See below.*) With further crystallization the fluid cells became smaller and more tenaciously held in place by the crystal-mesh. It seems entirely possible that liquid cells in small total proportion are now so held, ensuring weakness for the asthenosphere, even though there be a slow diffusion of the more volatile, supercritical component toward the earth's surface. Conceivably such diffusion is slowly accumulating juvenile gas under the tight, holocrystalline crust of the planet.

Sosman (1938, p. 359) has carried the two-phase idea still further, suggesting that even gaseous, inter-crystal films, a few molecules in thickness and held firmly attached to the crystals by adsorption, may be a good reason for great weakness in a peridotite which has been cooled down to a temperature as low as 550°.

The writer knows of no experimental evidence that the imagined two-phase asthenosphere should have zero strength, or that it should not have the small strength deduced for the actual asthenosphere by Barrell (1915, p. 43) and Jeffreys (1929, p. 201) from their studies of isostatic anomalies.

TEMPERATURE

In the 1942 earth-model the temperature at the depth of 70 kilometers in the earth was put at 1200°. Later a study of volcanism in Hawaii led to an estimate 100° higher—this in order to account better for the actual maximum temperature at which lava emerges at the surface of Mauna Loa. (*See* Daly, 1944, p. 1397.)[2] Let it be assumed that 1300° is the temperature of the thin, molten, basaltic substratum carrying some upward-diffused water and other gases in solution. Then a temperature of 1500° could be reasonably assigned to the 100-kilometer level, if the material there is a two-phase peridotite, also charged with volatiles in small proportion. Thus for the upper part of the asthenosphere a temperature of full white-heat seems to the writer to be indicated by a fact, namely the measured temperatures at active basaltic volcanoes.

Some geophysicists favor an earth-model of much lower temperature. For example, Jeffreys (1929, p. 154) prefers 1100° at the 100-kilometer level. This figure was deduced from various assumptions, including a law for the distribution of the heat of radioactivity in the depths of the planet. The actual law is, however, a mystery. Until the mystery is dissolved, it seems wiser, in estimating asthenospheric temperature, to let the facts of volcanism and their direct implications outweigh mathematical deduction from unsecured premises.

[2] Some of the heat in the flows may be due to chemical reactions induced after the gas-charged, basaltic melt approaches or reaches the surface.

VISCOSITY

Our two-phase asthenosphere is abundantly charged with molecular bonds stronger than those to be expected in an equivalent glassy layer, namely, the special bonds of the crystal-mesh. Hence the two-phase material should yield to a shearing stress much more slowly than a vitreous earth-shell under comparable conditions of temperature and pressure. The demonstrated high viscosity of the actual asthenosphere seems, in fact, to be more easily understood on the new view of the weak shell.

PROBLEM OF THE "450-KILOMETER DISCONTINUITY"

The rapid increase of V_p with increasing depth at about the 450-kilometer level below the earth's surface is not easily explained, if, according to the revision of the 1942 model, there is at this depth no downward transition from glass to crystalline rock. At the risk of being on the wrong track, a suggestion will be made—that we may here have to do with a second-order discontinuity, the locus of a rapid downward increase in the proportion of the speed-giving olivine (and possibly chromite or troilite or both) in the crystal-mesh.

PROBLEM OF THE "TRIAXIALITY OF THE GEOID"

In his 1943 article (p. 446) the writer touched on the question as to how the "permanent" ellipticity of the geoidal equator, deduced by some leading geodesists, could be reconciled with the postulate of zero strength in the asthenosphere. A conceivable answer to the question was found in the supposition that between the depths of 450 and 2900 kilometers in the globe the material is at its own upper limit elliptical at the equator and, because crystalline, denser than the asthenosphere and strong enough to keep the equipotential surfaces "permanently" triaxial. If, as suggested in the 1946 earth-model, the asthenosphere has finite strength, the difficulty of accounting for the supposed triaxiality of the geoid is diminished. The strength in the silicate mantle as a whole would be further supplied if the shell between the asthenosphere and the iron core is charged with few fluid (critical state) cells. The poverty in fluid cells at these depths is in its turn explicable if the material there is like a typical chondritic meteorite. This seems to give, on analysis, no more than a few tenths of a per cent of water or other volatile capable of resting in the critical state at the high pressure involved.

THE VITREOUS BASALTIC SUBSTRATUM

According to the revised model the earth has what may be fairly called a "true crust", even though the "substratum" of vitreous basalt may be not quite continuous around the globe. The uppermost "granitic" sublayer of the crust is "continental" and apparently not represented in about one third of the area of the deep sea. The underlying sublayer of "intermediate" rock is probably also discontinuous. The succeeding sublayer is pictured as truly world-circling and nearly twice as thick as the other two sublayers combined. This third sublayer is regarded as "gabbroic or eclogitic" but perhaps contains some injected peridotitic masses. The chemical composition of the glassy "substratum" is thought to be nearly the same as that of

the third crustal sublayer. The conditions for the vitreous state offer a vital problem whose solution will not here be discussed beyond the listing of some theoretical suggestions.

The first is appeal to periodical melting of the sima (basaltic earth-shell as a whole) by the heat of radioactivity—a hypothesis still retained by Poole (1930, p. 305; 1934, p. 9), though without satisfying argument.

Bowen (1928, p. 320) favors the idea that high-level chambers of molten basalt might be "currently" formed by the upward migration of such material after it—as a relatively low-melting constituent—has been squeezed out at the early stage of melting of deep-seated peridotite. He is, however, careful to point out (1928, p. 317) that "the fractional crystallization of meteoric matter would give the same result, so that the basaltic layer of a differentiated earth would be of essentially the same composition as the basalt formed by selective fusion". Bowen (1928, p. 317) shows that if molten basalt is thus "currently produced", the zone of this production has, during geological time, migrated downward—being now presumably at the depth of many hundreds of kilometers. If that be true, the risen basaltic material, though somewhat expanded and therefore cooled, should arrive at the base of the crust in a superheated condition; hence some melting of the "gabbroic or eclogitic" sublayer of the crust would be induced, with addition to the thickness of the vitreous substratum.

And a third, competing or supplementary, hypothesis may be worth consideration. We have already sensed the possibility that juvenile gas, rising from depth, may become concentrated under the relatively tight, holocrystalline crust. It is readily imagined that the resulting accumulations of gas have fluxed enough of the gabbroic or eclogitic sublayer to cause volcanism and even (ultimately) batholithic invasion all the way to the earth's surface. On this view extensive igneous activity would be terminated by temporary exhaustion of the supply of the subcrustal motivating gas. Hence theoretically the periodic nature of major igneous action can be understood, and the postulate of a two-phase character, and therefore great weakness, of the thick shell below the crust can be kept. If this shell is holocrystalline, as implied by an unmodified form of the Bowen hypothesis, the cause of its actual weakness is not manifest.

If the earth has undergone progressive cooling (with or without the interruptions demanded by the theory of "thermal cycles"), we should expect: (1) that the accumulation of either molten basalt or fluxing gas under the crust was formerly of comparative liveliness; and (2) that at earlier geological epochs the vitreous basaltic substratum was much thicker and more effective as source of world-wide igneous activity than at the present time.

CONCLUDING REMARKS

In review, it appears that there are good reasons for suggesting an amendment of the 1942 earth-model by the substitution of a dominantly two-phase asthenosphere for a vitreous asthenosphere, and by making some moderate changes in the assigned densities, temperatures, and pressures in the silicate mantle. According to the revised (1946) model the planet consists, in downward succession, of the lithosphere,

the vitreous, basaltic substratum (now perhaps discontinuous), a thick two-phase shell which with the basaltic substratum constitutes the asthenosphere, an underlying, more nearly holocrystalline shell, and the fluid iron core. The basal cosmogonic postulates—the mode of the earth's evolution and a composition indicated roughly by the averages for achondritic, "stony" (chiefly chondritic), and iron meteorites—are retained.

Incidentally we note that the density of the asthenosphere now comes out at about 5 per cent greater than that suggested in the writer's 1942 earth-model, which, therefore, to preserve a correct value for the earth's moment of inertia, should be amended by assigning a slight increase in the density for the deeper and more voluminous part of the silicate mantle about the iron core of the earth. The small changes in the figures for density and compressibility would not of themselves affect the validity of the idea that the earth as a whole has the composition of the average meteorite.

However, the foregoing paper is not a declaration of faith; it is an SOS call. Before it can be held definitively that a vitreous state for the whole of the existing asthenosphere is impossible, direct experiments on the viscosities and elasticities of a series of peridotite-glasses at high temperatures and pressures are necessary. Other high-pressure experiments on peridotites between liquidus temperature and solidus temperature are just as essential before the alternative hypothesis of a two-phase asthenosphere can be finally accepted. In addition renewed efforts should be made to establish still more closely the velocities of the seismic waves at depth, particularly in the earth-shells between the surface and the 100-kilometer level.

Although the postulate of a dominantly two-phase asthenosphere seems to be a good basis for understanding the low strength, the high viscosity and rigidity, and the response of this earth-shell to earthquake shocks, other correlations represent as many unsolved problems. Some examples: Can that asthenosphere be convectively overturned? What part has it played in orogeny, in the origination of magmas, in the invasion of the earth's crust by large masses of peridotite, and in the radioactive heating of the globe? To secure relevant answers to these and other fundamental, associated questions would demand a long program of difficult researches in the high-pressure laboratory.

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ENGINEERING APPLICATIONS OF AERIAL RECONNAISSANCE

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ABSTRACT

The development of aerial photography and the extensive coverage that has been accomplished in recent years has stimulated the use of airphotos to facilitate engineering planning and construction. The basis of this phase of development has been the identification of features that bear a relationship to the texture of the soil pattern although they include such elements as land form, drainage, soil color, erosion, and vegetative cover. Land form identification does much toward establishing general conditions of soil depth and texture, while surface drainage indicates relative permeability. Gullies assume various shapes and thereby reveal not only certain properties of the surface material but the existence of clay-pan developments or unrelated materials occurring below the surface. Soil color is related to texture and ground water conditions, and vegetation is a variable depending upon climate and local influences.

Assembled evidence shows that most soils can be distinguished by characteristic patterns regardless of their geographic distribution. Photographs illustrate the similarity of patterns, and test data are presented to permit the evaluation of interpretation.

The use of this information contained in airphotos enables design and construction practices to be established in the early phases of planning peacetime construction or military operations. Grading estimates are made with varying accuracy,

depending upon the quality of photography and equipment available, but detailed clearing estimates can be made from uncorrected photographs.

INTRODUCTION

The application of photo-interpretation to engineering work is predicated on the belief that construction and design problems are related to the physical properties of surface or near-surface materials and that these physical properties largely determine the weathering characteristics of the earth and rock materials.

The features that influence or are influenced by physical properties can be organized and applied in a logical manner; they are classified into: land form, drainage, erosion, color, and other minor indicators that include vegetation. These elements vary in intensity and in some areas may not be present, but the wide perspective available in airphotos largely overcomes this difficulty.

LAND FORM

The most general element should be identified first, since it establishes the general properties of the materials to be encountered. In some instances, identification of the land form is sufficient to establish texture and drainage or other properties. Examples of such land forms are (1) dunes, limited to a narrow range in the sand grain-size distribution; (2) kames and eskers, containing graded sand and gravel mixtures; and (3) loess, a material falling within a restricted range in the silt grain-size distribution. In most instances, when the land form is established the type of material that can occur in that particular form is automatically restricted.

DRAINAGE AND EROSION

The amount and type of surface drainage on these land forms is obviously related to slope and permeability of a land mass. Where there is a large amount of surface drainage on level to undulating relief, the soil material can be expected to be relatively impervious, while a lack of surface drainage indicates a porous land mass. Recent alluvium is an obvious exception since it is periodically refreshed by overflow.

Not only does the presence of surface drainage indicate retarded internal drainage, but there is more to learn from the drainage pattern. Passing over the better-known influences on drainage caused by the presence of bedrock, there are other interesting characteristics of gullies and drainage ways. These erosion features possess distinctive characteristics depending chiefly on the texture of the soil materials that are being eroded. Gully shapes both in cross section and profile are indicative of texture.

Earth materials, such as ice-laid drift and valley trains, that can be described as slightly cohesive are marked by short, sharp-edged, V-shaped gullies having a steep but rather uniform gradient from head to foot. In contrast gullies in plastic, cohesive soil materials have long, low, uniform gradients. In cross section these gullies will have well-rounded, sloping sides (Figs. 1, 2). Where these characteristics change somewhere in the length of a gully, a change in the soil profile is indicated. Where gullies erode through a surface mantle and encounter a deep and contrasting substratum, the cross-section shape will change. Erosion features of sand-clays and

silts have distinct and individual characteristics; their gullies, for instance, have a compound gradient and are generally U-shaped in cross section.

Since these features are impartially recorded on an aerial photograph an interpreter can make a deliberate and detailed study of this and other e ements of the soil pattern.

COLOR

Like the other elements in the soil pattern, color is only a relative indicator of texture. Each element by itself is ordinarily insufficient evidence on which to base a judgment of texture; therefore, it is desirable to examine and evaluate each of these elements present in an area. This is usually practical since a single photograph will record nearly 10 square miles of area. Light color tones are usually associated with well-drained soils, while clays, principally because of their water-retention capacity, appear dark. Well-drained silts, sands, and sand-gravel mixtures appear as light tones on aerial photographs. Figure 1 of Plate 2 shows the critical response of soil color to moisture content. Such color values are often ascribed to vegetation and cover crops. While surface cover obviously will tend to obliterate a soil color there are few cultivated crops sufficiently extensive and dense to obscure entirely, the trend of the pattern. This condition is shown in Figure 2 of Plate 2.

Vegetation is a product, not only of soil and climate but of soil-climate—*i.e.*, the same soil material occurring on different slopes will have different moisture contents. This is particularly important in tropical regions where long seasons of high rainfall are common. While the general impression gained from flying over a rain-forest area is one of monotonous uniformity, examination of airphotos of the same area will show definite vegetative patterns following corresponding trends in soil or drainage conditions. In spite of high rainfall in the tropics, gravels and sands in well-drained positions will have a "dry" soil-climate in contrast to other textural combinations found in association with them. At the other extreme the dry climate of northern interior Alaska includes areas having a wet soil-climate regardless of texture. These are coincident with the areas of perennially frozen ground, and here vegetation changes accordingly. Consequently, in areas where the ecologic balance is undisturbed, vegetation will reflect subtle changes in the soil-climate (Pl. 3, fig. 1).

Combining these various elements of the soil pattern and interpreting them in the light of experience and principles that are universally applicable makes airphoto interpretation a medium of obtaining and presenting information regarding the physical properties and conditions of surface materials.

Engineering intelligence whether as a military unit or an integral part of the planning and execution of engineering contracts is one and the same function. In either case, the amount of time needed for field investigation is far out of proportion to the time allowed. The application of aerial reconnaissance to these problems does much to bring these back into a workable adjustment, for it immeasurably expedites field work and provides details on the type and quantity of clearing as well as on the type of material to be excavated.

To illustrate some of these features a number of soil and rock materials having special interest are included.

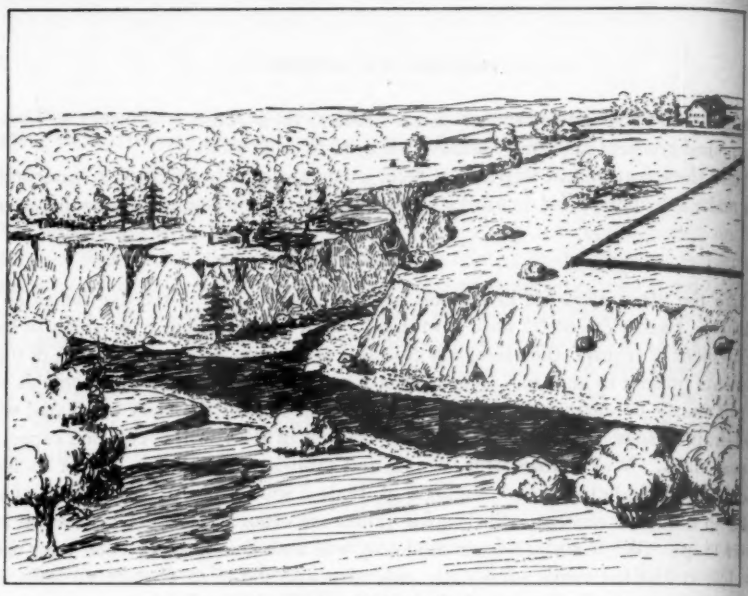

FIGURE 1.—*Typical gully form*

Showing the simple form of a well-developed, V-shaped gully. The steep sides, lack of tributaries, and the rather sharp downward break from the original land surface are characteristic. Incipient gullies in the form of notches or erosion scars are typical occurrences. (*Cf.* Figure 1 of Plate 1.)

FIGURE 2.— *Gully type typical of "clay lands"*

This sketch implies the presence of a serpentine channel course; a long, low gradient; numerous well-developed tributaries; and well rounded sloping sides. (*Cf* Figure 2 of Plate 1.)

FIGURE 1. LOOKING TOWARD THE HEAD END OF A V-SHAPED GULLY
Steep side slopes and steep, but relatively uniform, gradient are apparent. Where the skyline can be seen through the trees, cultivated fields on undulating relief border the gully (Vermillion Co., Ind.).

FIGURE 2. LOOKING TOWARD THE MOUTH FROM THE MID-POINT OF A GULLY IN GLACIAL LAKE SOURIS
(Ward Co., North Dakota)
Rounding of upper edges, well-developed tributary system, and tortuous course are evident.

GULLY FORMS RELATED TO PHYSICAL PROPERTIES OF SOIL MATERIALS

FIGURE 1. INFLUENCE OF A POROUS SUBSTRATUM ON THE SOIL COLOR
In this generally impervious area, fine, white lines coincide with pattern of 4-and 6-inch field tile, buried at depth of approximately 4 feet. These buried tiles act as effective subdrains, much as a sand or gravel substratum does (White Co., Indiana).

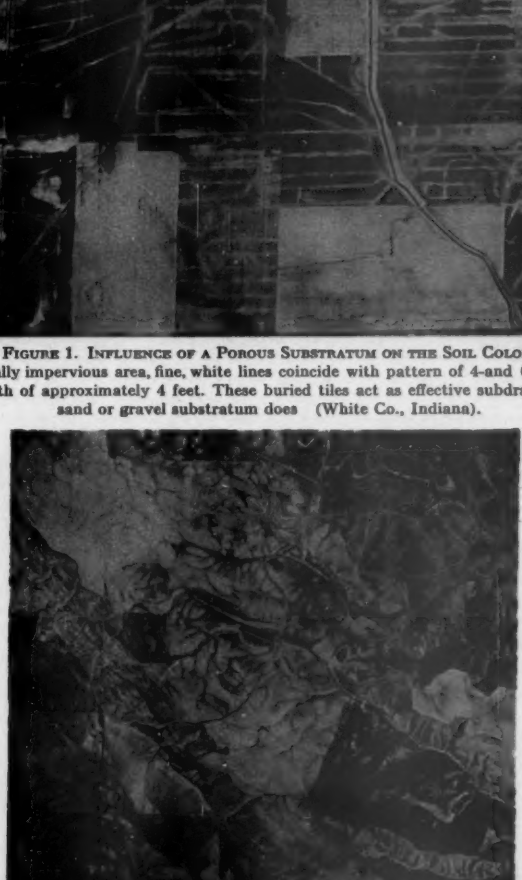

FIGURE 2. AREA OF CLAY SHALE IN CALIFORNIA DEVOTED TO RELATIVELY DENSE GRASS AND GRAIN CROPS
Removal of clay-sized material from hill slopes and the corresponding accumulation in drainage ways creates a strong color contrast in this soil area. Soil color is attributed to those dark irregular areas generally associated with drainage lines. Broad dark areas with well-defined, regular border are field and crop patterns; in these, soil colors are also visible but less distinct (Kern Co., California).

INFLUENCE OF DRAINAGE AND TEXTURE ON SURFACE COLORING

TERRACE GRAVELS

While a terrace, as such, may contain a wide variety of soil materials ranging from silty clays to gravels, the way in which it weathers will be related to the texture of the material. Gravel deposits in the terrace form are recognized by a marked absence of surface drainage. Where erosion occurs along the face of the terrace the gullies are short, sharp, and V-shaped appearing much as notches cut in the definite edge that is also a characteristic of these gravel forms. These and other level-lying gravels develop a form of microrelief that may be termed "infiltration basins" for it is into these that surface water tends to collect and filter into the porous subsoil.

Most of these features can be observed in Plates 4 and 5, which illustrate the occurrence and appearance of gravel terraces in New Zealand, New Guinea, Alaska, and the Middle Western States.

LOESS

Many loessial areas are marked by a land form that can be described as parallel hills. Closely associated with this feature established during deposition is the drainage pattern and the type of erosion characteristic of silt textures (Pl. 5, fig. 2). While the concept of parallelism in the hill pattern is apparently unorthodox it is worth while to note that this land-form pattern is a distinct feature in many counties in the loess area along the Mississippi and Missouri rivers, in the Palouse country of Washington, and in related areas in southern Idaho.

In few areas is this land form better illustrated than in the Loveland loess of north western Nebraska; it exerts only a subtle influence on the pattern in the Sioux Falls area of South Dakota where loess overlies Kansan drift at relatively shallow depths.

In such areas, especially where the terrain is rolling, a large amount of excavation and embankment is required in roadway or runway construction. Since silt, because of its grain size, is highly unstable at moisture contents in excess of the optimum[1], the early identification of these deposits in an area is necessary. Since the onset of wet weather in these areas will stop construction overnight, this type of information is important to administrators, bonding companies, and others who may never see the project, as well as to contractors bidding or working in unfamiliar areas.

The uniformity of loessial materials may be an expected characteristic. Despite minor exceptions to this uniformity, random sampling reveals a surprising similarity in widespread deposits as measured by standard tests (Table 1).

LIMESTONES

Where limestones are sufficiently soluble to form sinkholes (Pl. 3, fig. 2), they give rise to residual soils that have common physical properties. The soil and the many special problems associated with this rock type make limestone areas unusual. Except for possible surficial deposits of drift or loess on limestone, the identification of sinkholes establishes the land form and in general fixes the texture and profile char-

[1] Reference is to Proctor's optimum: that moisture content at which a maximum density is obtained under a given amount of compactive effort.

TABLE 1.—*Representative samples of loessial soils from various deposits*

Approximate location	Liquid limit	Plasticity index	Dry weight*	Class†
Weathered Portion of Profile (A and B horizons)				
Iowa, Eastern	38.8	17.0	—	9
Missouri, Eastern	33.6	16.3	—	9
Iowa, Western	43.2	17.9	—	9
Missouri, Western	40.5	15.9	—	9
Washington, Southeastern	34.5	12.1	—	9
Kansas, Western	31.7	12.5	—	9
Utah, Idaho Line	36.1	7.5	—	9
Indiana, Southeastern	41.2	16.5	101.8	9
Illinois, Western	53.6	30.2	—	11**
Mississippi, Western	45.5	16.8	—	9
Tennessee, Western	38.4	11.8	104.2	9
PARENT MATERIAL (LOESS)				
Kansas, Western	(Textural and inspection classification)			6
Washington, Southeastern	30.7	7.5	99.5	6
Indiana, Southeastern	29.2	7.3	109.0	6
Tennessee, Western	29.0	4.9	104.5	6
Mississippi, Western	31.8	3.1	104.5	6
China, Northern	—	6.1	—	6††
Washington, Southeastern	38.9	13.4	—	9
Missouri, Eastern	33.6	16.3	—	9

* Lab. Max. at Proctor's Optimum. † Joint Highway Research Project classification. ** Depression. †† Classification based on plastic limits.

TABLE 2.—*Representative samples of some limestone residual soils*

Approximate location	Liquid limit	Plasticity index	Dry weight	Class
Oklahoma, Central	51.0	30.6	—	11
Missouri, Southwestern	38.6	18.8	—	10*
Kentucky, Central	59.1	20.3	92.8	11
Ohio, Eastern	62.6	42.6	81.2	12A
Oklahoma, North Central	60.0	40.9	—	12B
Kansas, Southeastern	56.8	28.4	—	11
Alabama, Eastern	69.3	27.6	86.0	12A
Ohio, Southeastern	65.0	35.5	—	12A
West Virgnia, Northwestern	54.1	31.7	97.7	11
Arizona, Central	57.4	33.9	—	11
Wisconsin, West Central	83.8	57.2	84.0	12A
Utah-Arizona Line	58.1	39.3	—	12A
Indiana, South Central	63.6	29.5	82.5	12A
Puerto Rico	61.8	26.2	—	12A

* Has a high chert content.

acteristics of the soil mantle. The general textural properties as indicated are rather uniform (Table 2).

FIGURE 1. VERTICAL VIEW OF A TROPICAL AREA ILLUSTRATING CONTRASTS SOMETIMES FOUND IN VEGETATION

Ecologic balance is well established in an area where conditions vary from place to place. From the black ocean area (upper left) to the high hill country (lower right), definite bands of vegetation mark: (1) coconut trees on a well-drained sand ridge, (2) salt-water swamp — mangrove, (3) fresh-water swamp — nipa palm, and (4) well-drained upland slopes with a mixed vegetative cover (Geelvink Bay, Dutch New Guinea).

FIGURE 2. EXAMPLE OF HIGHLY DEVELOPED SINKHOLE TERRAIN.

Soil materials included in Table 2 were obtained from limestones in various stages of weathering (Harrison Co., Indiana).

EXTREMES IN AMOUNT OF VEGETATIVE COVER

FIGURE 1. WIDE EXPANSE OF GRAVEL TERRACE IN NEW ZEALAND SHOWING THE UNDISSECTED TERRACE FACE AND LACK OF CROSS-DRAINAGE
Infiltration basins can be seen as small dark areas in the fields (foreground) (Courtesy, New Zealand Mapping, Ltd.).

FIGURE 2. STEREO-PAIR OF VERTICAL PHOTOGRAPHS SHOWING HIGH-GRAVEL TERRACE IN ALASKA
Lack of surface drainage and short, notched gullies are apparent. Although covered by dense second growth, old channel scars on terrace surface are obvious (Courtesy, U. S. Engineer Department).

FIGURE 3. UNDISSECTED, GRASS-COVERED, GRAVEL PLAIN IN THE EAST-CENTRAL NEW GUINEA
High rainfall has failed to develop surface drainage on the plain. In lower left, the well-defined terrace face is unscarred by erosion.

GLACIAL DRIFT—TILL PLAINS

From an engineering standpoint the soils produced by weathering of the till plains are good examples of similar soil profiles recurring on similar slopes. The obvious relationship among relief, drainage, and soil color is well illustrated in the late Wisconsin till plain (Pl. 6, fig. 1). Experience and the aerial photos enable one to anticipate, within a tolerance of approximately 10 inches, the depth to the parent material —the relatively unweathered till.

In the Illinoian drift areas the soil profiles present a strong contrast to those found in Wisconsin drift. Corresponding to this physical change the soil pattern also shows differences in drainage, erosion, and color. This difference is so sharp that, in many places where they meet, the boundary between these two drifts can be defined (Pl. 6, figs. 2, 3) within a few hundred feet. Where thin drift overlies other materials such as limestone the underlying material will influence the pattern by the addition of elements related to the underlying material. In the Illinoian drift in Ohio the relief, color, and erosion features are similar to those in the Illinoian drift regions in Indiana and Illinois. In all areas the presence of clusters of sink holes along the eroded channels indicates the presence of buried limestone bedrock—an important feature that would probably not be detected by a location or soil survey party.

The short review of this technique has been an attempt to show the correlation between air-photo patterns and engineering problems and that the application of aerial photography to these problems is not restricted, either geographically or climatically.

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FIGURE 1. VERTICAL VIEW OF A WIDE PLAIN
Myriad of small, dark, irregular spots that act as basins distinguish this as gravel material. Sand terraces do not develop this feature because of their resistance to weathering (Elkhart Co., Indiana).

FIGURE 2. VERTICAL VIEW OF LOESS AREA IN MISSOURI ILLUSTRATING GENERAL TENDENCY OF HILLS TO BE ORIENTED INTO A SYSTEM OF PARALLEL RIDGES
Water supply, compaction problems, and drainage installations are directly related to the land form and the texture of the soil material.

CONTRASTS CAUSED BY DIFFERENCES IN LAND FORM

FIGURE 1. SOIL PATTERN COMMONLY DEVELOPED ON THE SILTY-CLAY SOILS OF THE WISCONSIN TILL PLAIN

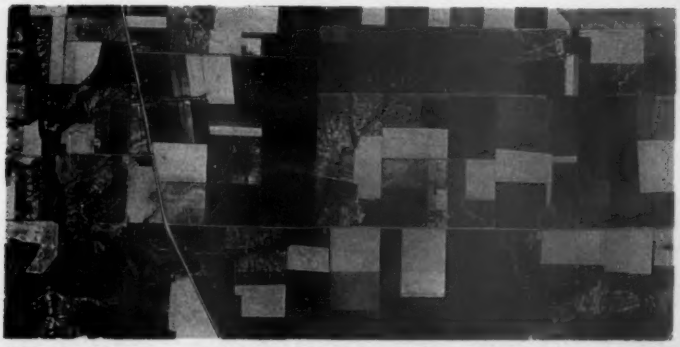

FIGURE 2. CHARACTERISTIC PATTERN OF ILLINOIAN DRIFT FOUND IN OHIO, ILLINOIS, INDIANA, AND MISSOURI

These are clay-pan soils having a silty topsoil (*A* horizon) and deep plastic material in the (*B* horizon) subsoil.

FIGURE 3. WHERE DISSIMILAR SOIL AREAS MEET, THE DEVELOPED PATTERN DENOTES CHANGING SOIL CONDITIONS

Boundary between Illinoian drift (left) and Wisconsin drift (right) can be clearly defined. Age difference between these two drift sheets is most significant variable.

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CORAL REEFS IN THE GILBERT, MARSHALL, AND CAROLINE ISLANDS

BY L. E. NUGENT, JR.

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ABSTRACT

The 77 atolls, 35 banks, 21 lagoonless coral islands, 5 reef-encircled volcanic islands, and 2 raised "phosphate" islands in the Gilbert, Marshall, and Caroline groups extend from 132° to 177° East Long. and from 15° North to 3° South Lat. The seamounts

are located on three types of submarine trends: The Gilberts, Ralik and Radak chains of the Marshalls, and eastern Carolines lie on gently arcuate trends with each member perched as an individual; the west-central Carolines evidence no regional alignment or arrangement but lie on a broad rise 1000 fathoms high; Yap and Palau are small island arcs. The submarine slopes of the seamounts average from 25° to 35° for the upper 1000 fathoms.

The Gilbert atolls are abnormally shallow and manifest slight regional tilting and excessive variation of reef width from windward to leeward. Aranuka has a bank at lagoon depth that extends several miles beyond the western reef margin.

The Marshall atolls exhibit remarkably uniform reef widths and lagoon depths. Kwajalein has a lagoon area of 663 square miles. Aur is tilted to the south and evidences no detrital filling or leveling; Eniwetok has a current that affects only one fourth the lagoon, yet it is the same depth throughout.

In the Carolines, Zohhoiiyoru, Kapingamarangi, Oroluk, Nomwin, and Murilo have abnormal lagoon floors that condemn detrital leveling; Ngatik, 87 fathoms, and Nukuoro, a "two-story" atoll, in turn condemn detrital filling. In the west-central Carolines none of the banks lie under more than 50 fathoms, and Gray Feather and Mogami, the two largest, are separated by a narrow shallow passage with rim reef growth on each side, evidence incompatible with the sheath-like coral growth that should accompany major subsidence. The reef-encircled volcanic islands have truncated spurs and cliffed shorelines; reef widths and lagoon floors are normal.

The accordance of lagoon and bank depths, the uniformity of reef width, the absence of inboard detrital slopes, pass notches, and outboard deltas, the general absence of coral causeways or piers, the angularity of shape, the demonstrated inefficacy of detrital filling and leveling, and the presence of truncated spurs and cliffed shore lines all indicate seamount truncation during the Pleistocene.

INTRODUCTION

For over a century coral reefs have presented some of the more contentious problems of geology. The remoteness of the areas of study, the difficulties and paucity of intensive field work in the tropics, and the lack of accurate topographic and hydrographic surveys have all delayed solution. Under such circumstances it is not surprising that the hypotheses advanced on incomplete, and frequently conflicting, data should be as divergent as the elementary tenets held by the originators. The result has been a voluminous literature on reef origins, not only because of the controversial and speculative nature of the subject, but also because of the special difficulty presented by these extraordinary barrier and atoll reefs.

The various hypotheses of origin have found enthusiastic supporters and polemic dissenters. Further, these hypotheses have enjoyed phases of acceptance and rejection as the results and opinions of later investigators have been added to the assemblage. Darwin's (1842) theory of reef growth on subsiding foundations, formulated after his voyage on the BEAGLE, and fully presented in 1842, was the first to explain adequately the relationships of fringing, barrier, and atoll reefs. His theory was widely acclaimed and given increased stature through Dana's (1849) observations on embayed shore lines during the Exploring Expedition in 1841. Murray (1880), Guppy (1890), Agassiz (1903), and others contended that reefs owed their positions to upgrowth or outgrowth from truncated or aggraded rising or stillstanding foundations. Daly's (1915) Glacial Control theory, presented completely in 1915, feasibly accounted for the accordance of depths and the level lagoon floors as well as reef

positions. Davis' (1928) exhaustive and comprehensive book *The coral reef problem*, published in 1928, effected a compromise between Darwin and Daly in the marginal zone. Yet it strongly recommended instability, and therefore subsidence, as the prime factor.

In spite of the fact that a satisfactory explanation of atoll formation is the ultimate goal of most coral-reef research, very little has been written of the Gilbert, Marshall, and Caroline islands, even though these groups present the most remarkable assemblage of atolls in the world, both from viewpoint of size and geographic range. The reasons for this have been many: (1) As Davis repeatedly stated, little could be learned of the origin of atolls from a study of atolls only; (2) the immense distance involved served as a natural deterrent; and (3) the lack of economic significance made these atolls decidedly unattractive to steamer traffic. As a result coral-reef literature is notable for the scarcity of data on these groups; Daly in his tables lists 8, and Davis in his treatise considers only 11.

During the war, however, these atolls provided excellent strategic bases both for fleet anchorages and coral air strips. Thus, an unprecedented opportunity for the study of reefs has been presented. The tens of thousands of aerial photographs and the accurate hydrographic surveys leave little to be desired. The new data on the reef-encircled volcanic islands in the Carolines, accompanied by the lagoon studies of the three island groups, permit evaluation of the competing theories of origin.

ACKNOWLEDGMENTS

The writer is particularly indebted to Mr. S. W. Stone and Mr. R. R. Phillips for aid in the preparation of this paper. Stone compiled practically all of the statistical data on the Marshall Islands, and Phillips aided greatly with the Caroline Islands. Especial appreciation is due Professor Daly for his critical review and suggestions concerning the final form. The paper, most of which is based on classified data, was released by the United States Navy.

REGIONAL DISCUSSION

The Gilbert, Marshall, and Caroline islands occur as pinpoints in a vast, and otherwise uninterrupted, expanse of the western Pacific. In the three groups there are a total of 77 atolls, 21 lagoonless coral islands, 2 raised "phosphate" islands, approximately 35 banks, and 5 reef-encircled volcanic islands. They extend from 152° to 177° East Long. and from 15° North to 3° South Lat. With few exceptions, they were little and imperfectly known to American geologists until the third year of the Pacific war.

Although the Gilbert Islands have been described in various journals and travelogues, the reefs have remained little studied except by members of the United States Exploring Expedition and a few British survey vessels. The Gilberts are not discussed in any of the major works on atolls or reef relationships.

Most of the Marshall atolls were carefully charted by Japanese survey vessels after the mandated islands were placed under their jurisdiction. In addition, several Japanese geologists and geodosists investigated the islands: Matsuyama (1918) de-

termined the value of gravity on Jaluit atoll, and later, on the same atoll, Yabe and Aoki (1922) found in a conglomerate a limestone pebble that contained Miocene fossils.

Although the Caroline Islands have been the subject of study for over 50 years, the volcanic islands, by comparison, have received much more attention than the atolls and lagoonless coral islands. Palau, Truk, and Ponape have been frequently considered with respect to reef positions and theories of formation: Palau was first discussed at length by Semper (1881), and Hobbs' (1944) recent paper treats a number of the Carolines from the structural and petrologic viewpoint.

East and south of the foredeeps contiguous to Palau, Yap, and the Marianas the floor of the ocean is uniformly level (Pl. 1); excepting seamounts and well-developed trends, over 90 per cent of the area is between 2000 and 3200 fathoms. Northwest of this demarcation the ocean floor is interrupted by two broad rises parallel to the Marianas. Although any discussion of structural and petrologic relationships is outside the scope of this paper, this demarcation, as far as known, also separates the basaltic province to the south and east from the andesitic rocks in the arcs.

The levelest section, and one of the deepest, is a belt 400 miles wide and 1200 miles long that lies north of the Carolines and Marshalls. This expance is broken only by a few isolated submarine volcanoes, and except for the slight rise north of the Marshalls it continues uninterrupted to the incompletely sounded area east of the Marshalls and Gilberts.

Although the area immediately west of the Gilberts has been least sounded, with the exception of Ocean and Nauru islands, it is apparently level and uninterrupted by seamounts or trends, a counterpart of the above-described areas. Farther west a low broad nose extends from the Solomon Islands northwest toward Truk. Next to this lies another level region at about 2500 fathoms, bisected by a broad rise that reaches from the Bismarck Archipelago north to the west-central Caroline rise.

There are three well-defined foredeeps. Nero Deep, one of the great arcuate troughs, lies on the east, southeast, south, and southwest sides of the Marianas and has a logged depth of 5366 fathoms. The trough is abruptly constricted north of Ulithi which prevents any connection at depth with the smaller Yap deep. Although the north end of the trough has been inadequately sounded, it apparently terminates in a flare. Except for the steep slopes south of Guam, where there may be another constriction, the northwest side of the trough slopes more gently than the southeast. In addition, the southeast side exhibits an excessively crenulate condition in the Saipan-Guam sector. Although the symmetry of the rise on the east side of the trough is based on incomplete data, the rather unorthodox presentation is considered justifiable because the disposition of soundings indicates a gently dipping plateau rather than isolated submarine volcanos.

The Palau and Yap trenches lie en echelon. Although the subtended sections are much less extensive than Nero Deep, the arcs are apparently of similar radii. The Yap deep, slightly smaller than Palau, has a depth of 4122 fathoms as compared to 4450 fathoms at Palau.

Three distinct types of submarine ridges are evident. The first type is illustrated by the Gilbert Islands, the Radak and Ralik chains of the Marshall Islands, and that

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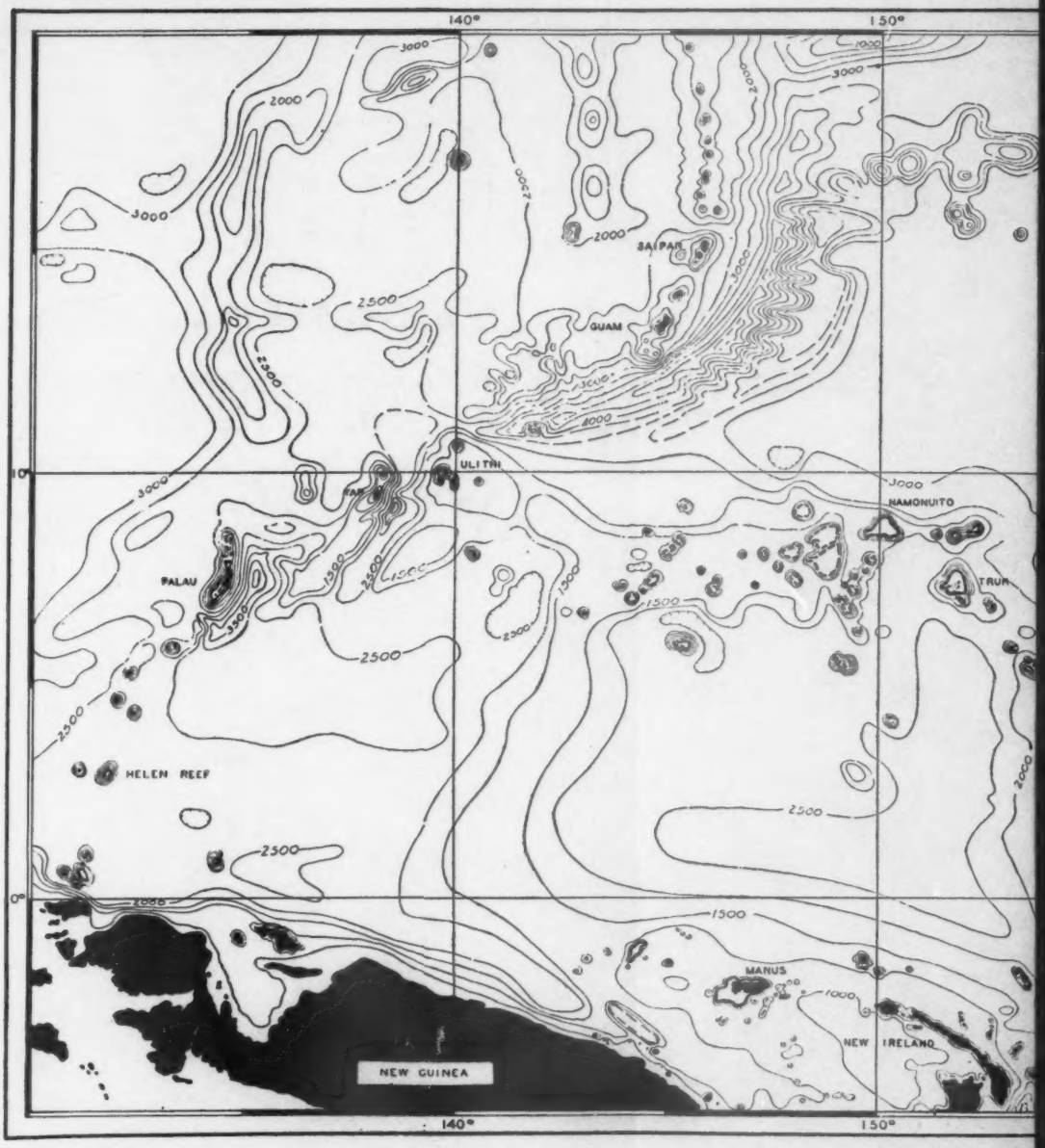
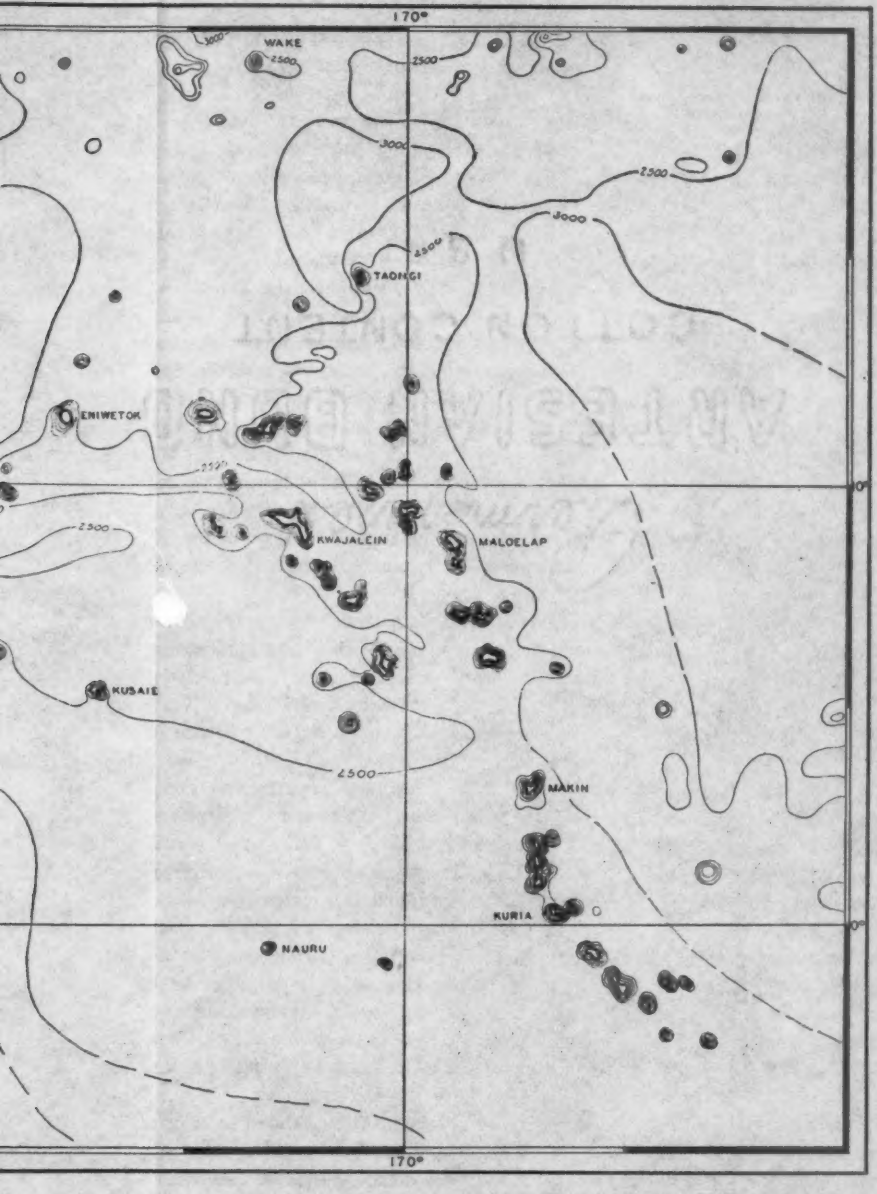


BATHYSPHERIC CHA

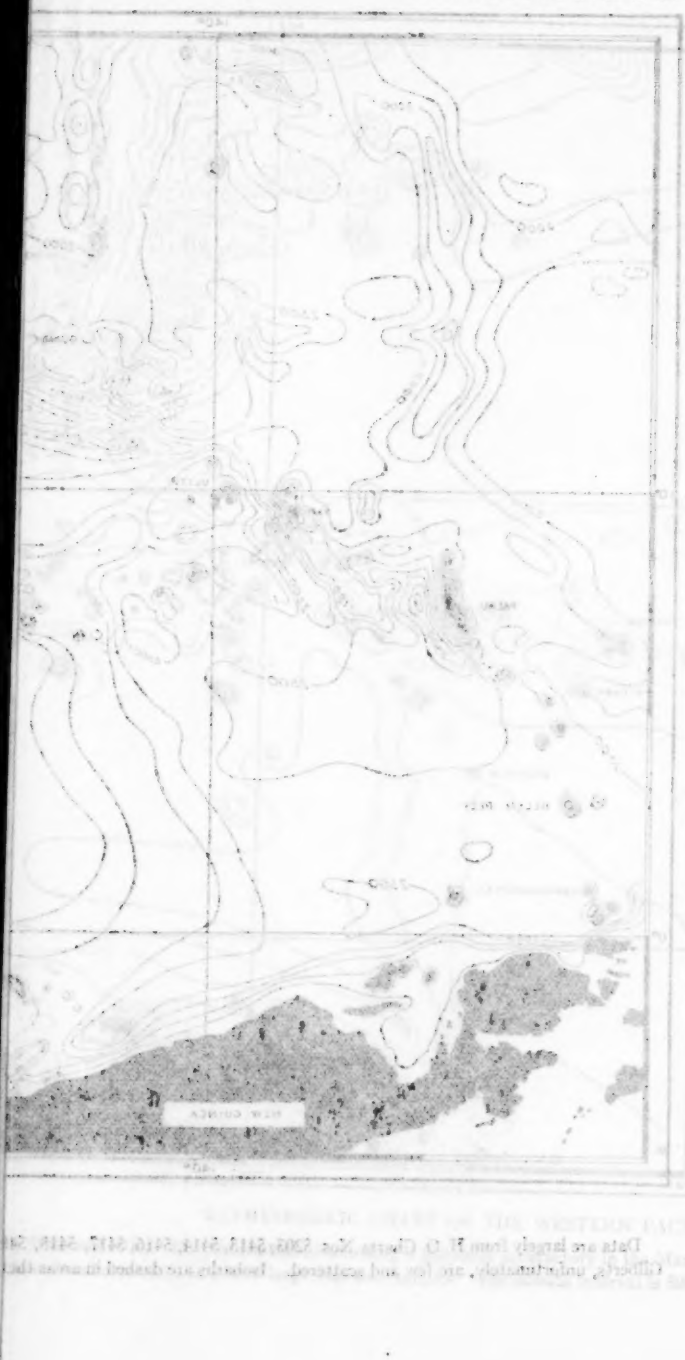
Data are largely from H. O. Charts Nos. 5203, 5413, 5414, 5416, 5417, 5418, 5486, 5590, and 5800. The distribution of sounding
Gilberts, unfortunately, are few and scattered. Isobaths are dashed in areas that have insufficient data to detect large regional fe

BATHYSPHERIC CHART OF THE WESTERN PACIFIC

18, 5486, 5590, and 5800. The distribution of sounding is generally satisfactory in the Marshalls and Caroline
as that have insufficient data to detect large regional features. The isobath interval is 500 fathoms.



lls and Carolines, north of these islands, in the Marianas, and north of New Guinea. Soundings in the thoms.


NEW GUINEA

section of the Caroline Islands which lies east of Truk. The Radak and Ralik trends are arcuate, convex to the northeast. The Gilberts are also arcuate, but convex to the southwest. The Caroline section is only very slightly arcuate. Although all four are strongly developed, each individual seamount rises abruptly from the level ocean floor. There is no evidence that contiguous atolls are connected by submarine ridges unless the atolls are in such proximity that their normal submarine slopes join. On the contrary, each seamount is perched upon the trend as an individual, to the extent that the major axes of some of the atolls are orthogonal to the regional trend.

Further, there are a number of isolated seamounts outside the chains with axial alignments unrelated to the regional structure. Since the ocean floor lies at the same relative depth between islands of one chain, between parallel chains, and outside the chains, there is little evidence of compressive stresses in these sections of the western Pacific.

The second type is found in a section of the west-central Carolines where there is a broad gentle rise about 200 miles wide and roughly 1000 fathoms above the surrounding ocean floor. Seamounts reach surfaceward from the rise with no evidence of regional alignment or arrangement. Similar structures are suggested by the trends west of the Marianas and the rise northeast of Nero Deep, although here no seamounts have reached the surface. From the bathyspheric data available no definite conclusions can be reached for the origin of such features. The rise may represent a low anticline, as Hobbs (1944, p. 239) has suggested for the Bonin-Kazan group. It might have resulted from an original variation in the composition of the floor; the proximity of the andesitic facies of the Marianas and Yap and the connection with the Bismarck Archipelago, also an andesite province, add weight to this hypothesis. Or, the rise could represent a vast extrusion of very fluid lava, and the seamounts could project from this lava plateau because of a change in composition of the magma.

The third type of trend is the island arc which lies concentrically within the foredeep. Palau, Yap, and the Marianas all exhibit in cross section characteristic asymmetry with steep dips to the trough and gentle dips to the concavity. The en echelon relationship of Palau and Yap indicates rotational stresses, the eastern stress apparently from the south, and the western from the north. The Mariana arc and Nero Deep, although seemingly associated with compressional stresses, do not afford much evidence concerning the mechanics involved. The crenulate condition of the east flank of the trough, however, may indicate that this section was the locus of the major compressional stresses combined with rotational forces.

All islands of the three groups lie within the trade winds or doldrums. The doldrums separate the northeast and southeast trades, and, like the heat equator, they are displaced slightly north of the geographic equator. All three belts "follow the sun" and vary in width seasonally; in February and March the doldrums are immediately north of the equator and are of inappreciable width, while in July and August they center at about 7° North Lat. and cover several degrees of latitude.

The trades blow with remarkable uniformity and intensity during late fall, winter, and spring, frequently with 20-knot velocities. In these longitudes, in spite of the fact that the eastern Marshalls are about 2500 miles from the Asiatic landmass, the

northeast trades are particularly influenced by the monsoon. This causes a marked diminution of velocity, and in September the wind may be from the southwest, a diametric change.

The southern Marshalls, northern Gilberts, and most of the Carolines lie within the doldrums during the monsoon months. Then winds sink to stagnation or light inconsistent breezes; the ocean surface is frequently mirrorlike in a flat calm. Obviously the contrast in the efficacy of wave action between the trades and doldrums is exceptionally marked.

As expected, each current of the west Pacific is confined to a wind belt. The north equatorial current flows within its generative belt, the northeast trades, and the south equatorial current in the southeast trades. The counter equatorial current sets east and is limited to the doldrums. A zone of relatively weak eddy currents is found between the north and counter equatorial currents and another between the south and counter equatorial currents. Most of the data concerning current velocities in the western Pacific are old; these placed the velocity of the counter equatorial current at approximately 2 knots, several times that of the north and south equatorial currents. Recent information, however, indicates that the three are more nearly similar with maximum velocities that approach 1 knot.

PRESENTATION OF DATA

The three island groups are presented separately. The Carolines, moreover, are subdivided into four sections: atolls, banks, lagoonless coral islands, and volcanic islands. Since it is impracticable as well as unprofitable to attempt a detailed description of each of the 140 members of the three groups, the pertinent data are tabulated.[1] Entries are listed according to size and have been assigned numbers in both the tables and text to facilitate reference.

Further, each anomalous atoll, especially those that bear on a theory of origin, is discussed at length and a number are shown on large-scale bathyspheric charts; because of the significance of the topography of the volcanic islands all five are included. In these charts coral islands are solid, and volcanic islands are stippled. Lagoon configuration is shown by 10-fathom isobaths, and exterior slopes by 100-fathom isobaths. Some submerged reefs are, however, indicated by 10-fathom isobaths. Coralheads have been omitted unless noteworthy.

GILBERT ISLANDS

The Gilbert Islands lie astride the equator; they extend from 3°20′N. Lat., 172°40′ E. Long., to 2°40′ S. Lat., 176°50′E. Long. Ocean Island (52′S., 169°35′E.) and Nauru Island (31′S., 166°55′E.) are uplifted atolls on which phosphate deposits occur. Although, for convenience, these two islands are frequently considered members of the Gilbert group, as far as known the only tie is proximity, and they are here excluded.

[1] All mensuration is based on the nautical mile (6080 feet). Dimensions are maximum outer reef. Lagoon areas were calculated by planimeter, and reef lengths by map measurer (road runner). Average depth was determined by sampling along representative lagoon sections. Evaluation of data is based on number as well as anticipated reliability. All charts referenced are United States Navy Hydrographic Office Charts.

In 1942 the enemy occupied the Gilberts without opposition in a campaign that was mounted from powerful bases in the Marshalls; an excellent airstrip was constructed on Tarawa, and Makin was utilized as a seaplane base. The amphibious operations of November 1943 completely ousted the Jap from the Gilberts; American airbases were built on Makin and Apamama, and the Tarawa strip was improved. These were used in preliminary interdiction of the Marshalls. The Gilberts have all been thoroughly covered photographically, and survey vessels of the United States Navy have carefully charted the better anchorages; the less important atolls and islands are still inaccurately known.

Table 1 presents the 11 atolls and 5 coral islands. The compiled data have been garnered from various sources and, as will be noted, are in several instances incomplete. Figure 1 shows the distribution of the group: eight atolls and three coral islands lie along the gently arcuate trend which is paralleled by the Ellice Islands 200 miles to the south. Although the major axes of Apamama (6), Beru (9), and Nukunau (12) parallel the chain, they are offset various distances; Maraki (11) and Tamana (16), the two remaining, do not conform.

In a comparison of the three island groups, the Gilberts present several anomalies. First, the atolls are the shallowest and show a definite decrease in depth southeastward; Makin (4) has an average depth of 15 fathoms, Abaiang (5) 12, Tarawa (2) 9, Apamama (6) 8, and Nonuti (1) 8. The easternmost islands are all lagoonless coral islands uplifted 10 to 15 feet. The Phoenix Islands, 700 miles to the east, also have shallow lagoons and evidence of recent uplift, but the Ellice group are for the most part normal.

Second, disproportionate reef development is strongly manifested. The reef islands are largely confined to the east (windward), where reefs are wide and continuous. Several of these are up to a mile in width; the wider ones rim the shallower lagoons. The leeward sides of the atolls show inferior growth; the reefs are both narrower and lower; Tabiteuea (3), Tarawa (2), and Apamama (6) exhibit only partially closed lagoons. In the Carolines and Marshalls reef widths generally average from 1500 to 2000 feet with much less variation from windward to leeward.

Third, several atolls and coral islands crown foundations that extend as shallow banks to the northwest, similar in position to Daly's (1934) bank insets. Figure 2 strikingly illustrates this at Aranuka Atoll (10) and Kuria Island (15). Although sounding was incomplete, the bank and lagoon depths are approximately the same. Also, Nonouti (1) has a bank on the west side estimated to be 5 miles wide, Maiana (7) apparently has one, and Beru (9) has a narrow bank on the southwest.

Figure 3 of Makin Atoll (4) has been included because the data are based on accurate hydrographic and aerial surveys. Though shallow, the lagoon floor is typically flat, reef development is slightly more regular than on the other atolls, and the passes are well defined. The slope off the southwest flank, the only gradient determinable in the Gilberts, is approximately 25°.

Of the five lagoonless coral islands Makin Meang (14) and Nukunau (12) have ponds in the center that are probably lagoon vestiges.

The Gilbert Islands afford some critical evidence applicable to the theories of coral reefs. The decrease in lagoon depths southeastward as well as the position of the slightly uplifted coral islands indicate minute regional tilting under any theory.

TABLE 1.—*Gilbert Islands*

Number, Name, Chart, and Co-ordinates	Maximum Dimensions (naut. mi.)	Lagoon Area (sq. mi.)	Maximum Depth (fms.)	Average Depth (fms.)	Reef Length (naut. mi.)	Reef Width (feet)	No. Passes	Lagoon Area/Reef-Length Ratio	Remarks
(1) Nonouti 2179, 121 40′S, 174°20′E.	10 x 23	133	20	8	56	5000	1	2.4/1	Poor reef development on southwest. Lagoon shallow with many coral heads-Old survey. Bank west of atoll?
(2) Tarawa 123, FC 34, 35, 36 1°28′N, 172°59′E.	13 x 19	100	14	9	50	3–6000		2/1	Partially enclosed lagoon. Discussed in text.
(3) Tabiteuea 119 1°24′S, 174°52′E.	8 x 32	?							Poorly surveyed. Lagoon open to west. Shoals also to west.
(4) Makin FC 37, 2179 3°7′N, 172°49′E.	15 x 18	74	28	15	49	3500	3	1.5/1	Discussed in text.
(5) Abaiang 123 1°50′N, 172°56′E.	14 x 16	69	15	12?	40	3000	5?	1.7/1	North end shallow with coral patches. Old survey.
(6) Apamama 122, 4001, 4002 22′N, 173°52′E.	6 x 13	42.5	15	8	30	5000	2	1.4/1	Numerous coral patches. Old survey.
(7) Maiana 122 55′N, 173°E.	12 x 13	38	5	5	30	6000	0	1.3/1	Shoal may extend NW. of reef. 3 soundings. Lagoon shallow. Old survey.
(8) Onotoa 119 1°51′S, 175°32′E.	4 x 11	15			24	6000	0	.6/1	
(9) Beru 119 1°20′S, 176°E.	3 x 9	8			18	3–6000	0	.45/1	Narrow bank west of atoll. Land-locked pond at each end. Lagoon shallow. Poor data.
(10) Aranuka 122	5 x 6	7.5			15	6000	1	5/1	Bank to west. Discussed in text. Old

1°20′S, 176°E.									locked pond at each end. Lagoon shallow. Poor data.
(10) Aranuka 122 11′N, 173°36′E.	5 x 6	7.5			15	6000	1	.5/1	Bank to west. Discussed in text. Old data.
(11) Marakei 122 1°58′N, 173°22′E.	2½ x 5	6.4?			12		0	.53/1	Poor data.
Lagoonless Coral Islands									
(12) Nukunau 119 1°23′S, 176°26′E.	2 x 9								Ponds on north end.
(13) Arorae 119 2°38′S, 176°49′E.	2 x 7.5								15 feet high.
(14) Makin Meang 121 3°15′N, 172°58′E.	2 x 7								Small ponds in center of two islets.
(15) Kuria 122 15′N, 173°24′E.	2 x 4½								Discussed in text. Old data.
(16) Tamana 119 2°29′S, 175°58′E.	1½ x 2½								

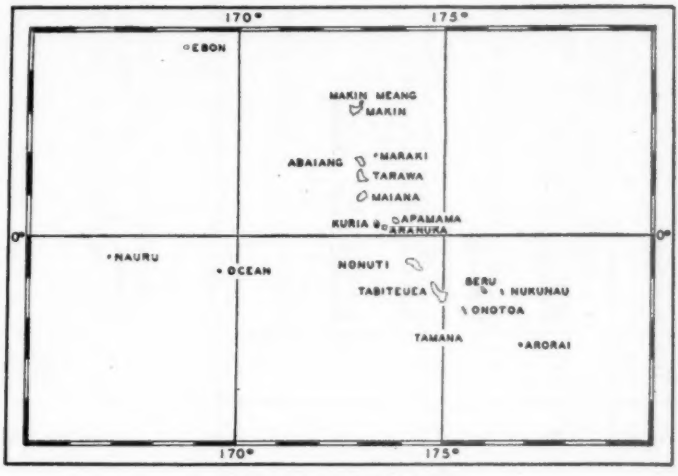


FIGURE 1.—*Gilbert Islands*

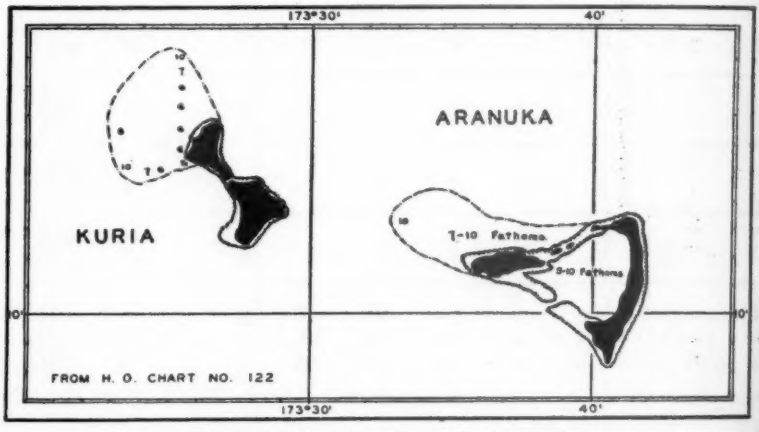


FIGURE 2.—*Aranuka atoll and Kuria Island*

Photographic studies of the lagoons of the shallower atolls show that coral-head growth is active; in some areas as much as half the lagoon floor is covered with live coral, and there is frequent evidence of head coalescence. Although the characteristics of lagoon floors of average depth are not known well enough to permit a positive comparison, it seems unlikely that any such percentage is covered by live coral, particularly in view of the paucity of coral heads at or near the surface, a fact, moreover, that does not favor the antecedent platform theory. Therefore, a critical depth may exist; when this depth has been attained by aggradation or uplift coral-

head growth may fill the lagoon quite rapidly. There is some indication that this depth may be 5–10 fathoms.

The abnormally wide reefs may be explained by a longer stillstand under the subsidence theory; under Glacial Control slight uplift shortly after truncation would

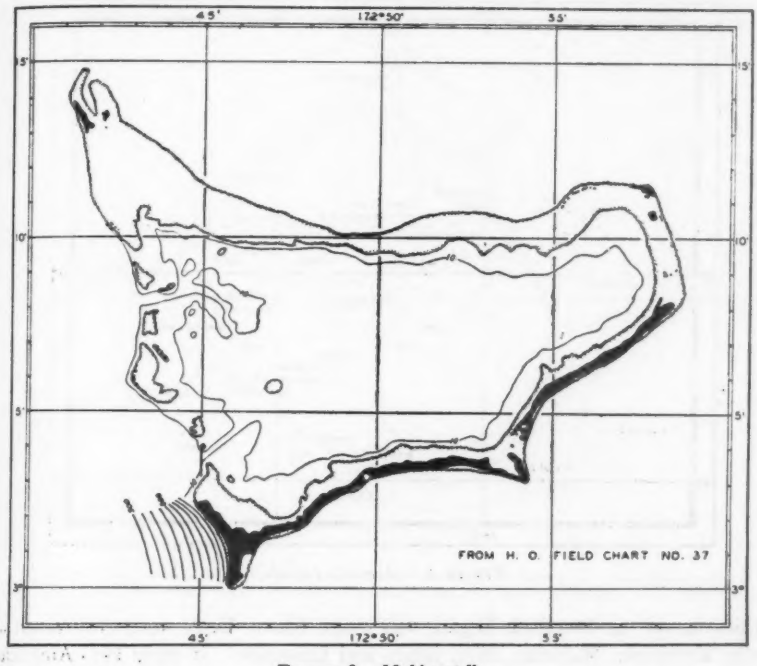


FIGURE 3.—*Makin atoll*

permit a greater proportion of reef growth outward. The presence of banks to the west of four atolls, however, is difficult or impossible to explain by subsidence. These banks are approximately the same depth as the lagoons and are separated from them by the reef wall. Detrital filling and leveling is practically precluded for the banks—two factors essential for the tenability of Darwin's theory. Occasional reef growth other than on the perimeter of a truncated foundation is not only easily compatible with Daly's theory but expectable.

MARSHALL ISLANDS

The Marshall Islands lie between 4° and 15° North Lat. and 160° and 174° East Long. and include 29 atolls, 5 lagoonless coral islands, and 1 small bank. All have been covered photographically and by excellent hydrographic surveys. Most of the atolls lie in two gently arcuate chains: the Radak Chain, the eastern, has 13 atolls and 1 coral island, and the Ralik Chain has 6 atolls and 2 coral islands (Fig. 4). The

remaining 10 atolls, 2 coral islands, and bank lie outside the chains and exhibit diverse alignments.

During World War I the Marshall and Caroline islands were seized by the Japanese and were subsequently awarded to Japan as a mandated territory. In the 1930s

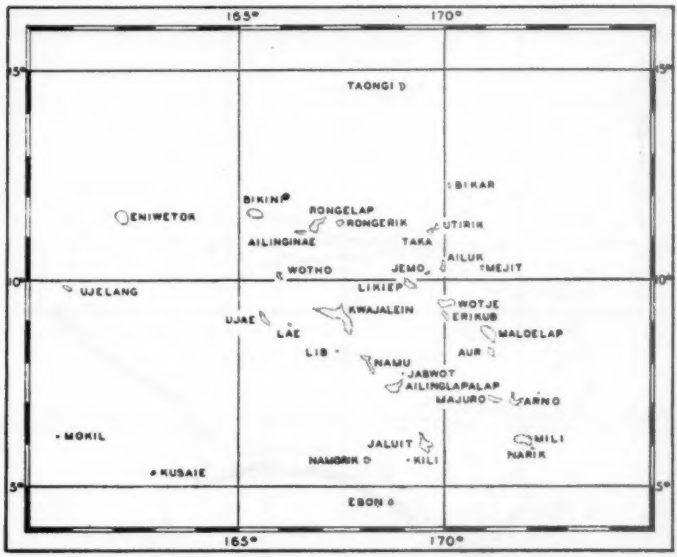


FIGURE 4.—*Marshall Islands*

fortification of the Marshalls began, and major enemy bases were constructed at Wotje, Kwajalein, Maloelap, Mili, Jaluit, and Eniwetok. In early 1943 American forces secured Kwajalein, Majuro, and Eniwetok, all of which served as bases for the Marianas campaign.

In size, reef development, and accordance of lagoon depths the atolls of the Marshall group are the most uniform in the world. There is no such windward and leeward variation as in the Gilberts; reef widths average from 1500 to 1800 feet. Bikini (25) with approximately 8 miles of drowned reef on the south side and Kwajalein (17) with several drowned sections on the southwest side are exceptions. Passes are generally confined to leeward, none of the atolls has an abnormal number, and there are no pass notches. Lagoon floors are exceptionally level, and reef walls are steep.

Kwajalein (17), with a lagoon area of 663 square miles and a reef length of 164 miles, is the largest atoll in the Pacific. Maloelap (19) and Aur (31), the deepest in the group, have soundings of 48 fathoms and average 31 and 28 fathoms respectively. The northern atolls of Pokaakku (39) and Bikar (42) with average lagoon depth of 7 and 10 fathoms, like Wake, farther north, are unusually shallow.

Eniwetok (20), the most symmetrical large atoll in the three groups, is approximately 20 miles in diameter and has a lagoon area of 280 square miles. Figure 5, based on excellent hydrographic data, shows that there are only two passes, both close together on the south and southeast sides, and that the windward reef is wider

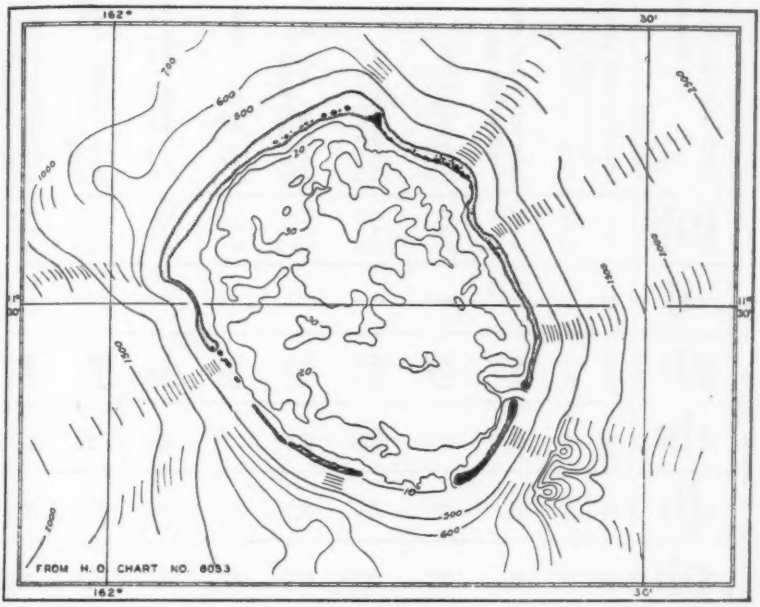


FIGURE 5.—*Eniwetok atoll*

and higher. Even though one main current streams through these passes that affects less than one fourth of the lagoon, the floor is level throughout. Further, wave action is unable to move detritus from windward to the lagoon because of the reef islands, a fact substantiated by the lack of a detrital slope on the east side of the lagoon.

Because of Eniwetok's symmetry and excellent survey an estimate is possible of the subsidence required under Darwin's theory. If subaerial erosion is neglected, and the average submarine slope to 1000 fathoms is extrapolated, the volcanic island would have had a theoretical elevation of approximately 20,000 feet. The effect of accumulation of volcanic detritus and the angle of reef ingrowth have been omitted because the Kazans and Nansei Shoto indicate that wave and current action may prevent sea-level detrital accumulation about seamounts in the open ocean and because the angle of coral growth is not well enough known. If it be assumed that erosion reduced the elevation by four-fifths, a very generous assumption, subsidence of approximately 700 fathoms is required.

TABLE 2.—*Marshall Islands*

Number, Name, Chart, and Co-ordinates	Maximum Dimensions (naut. mi.)	Lagoon Area (sq. mi.)	Maximum Depth (fms.)	Average Depth (fms.)	Reef Length (naut. mi.)	Reef Width (feet)	No. Passes	Lagoon Area/ Reef-Length Ratio	Remarks
(17) Kwajalein 11, 300–27 & 5428 9°10′N, 167°30′E.	43 x 50	663	34	27	164	1400	12	4/1	Soundings only in east half. 12 miles drowned reef on south part of west end.
(18) Rongelap 6029, 6030, 6031 11°20′N, 166°50′E.	17 x 30	305	37	28	80	1900	7	3.8/1	Relatively steep inboard. Soundings only on east side.
(19) Maloelap 6014, 6015, 6016 8°45′N, 171°00′E.	12 x 33	281	48	31	75	1500	8	3.8/1	Discussed in text.
(20) Eniwetok 6033 11°30′N, 162°15′	18 x 22½	280	34	25	64	1200	2	4.4/1	Discussed in text.
(21) Jaluit 6007 6°00′N, 169°35′E.	25 x 33	244	27	20	84	1650	5	3.1/1	Soundings only in southeast. Steep inboard slope.
(22) Ailinglapalap 6011, 6012 7°23′N, 168°45′E.	9 x 24	228	34	25	72	1800	5	3.2/1	Steep inboard. No soundings west end.
(23) Mili 6001 6°10′N, 172°00′E.	10 x 22	228	39	26	69	1800	5	3.4/1	Steep south; gentle north.
(24) Wotje 6017 9°25′N, 170°00′E.	9 x 27	203	39	27	64	1500	3	3.2/1	Steep inboard. Very steep east flank slope.
(25) Bikini 6032 11°35′N, 165°25′E.	11 x 22	192	35	26	57	1500	5	3.4/1	8 miles of reef on SE corner at about 7 fathoms.

11°35′N, 165°25′E.									fathoms.
(26) Likiep 6020, 6021 9°55′N, 169°05′E.	7 x 24	123	34	23	52	1500	4	2.4/1	Steep inboard on N., W., S.,—E. inboard slope gentle.
(27) Namu 6013 8°00′N, 168°09′E.	4 x 32	121	27	21	72	1400	3	1.7/1	Soundings only around southern pass.
(28) Arno 6004 7°05′N, 171°40′E.	7 x 17	109	34	26	78	2000	2	1.4/1	Steep on west and south.
(29) Majuro 5429 7°10′E, 171°10′E.	5 x 21	90	35	27	50	1400	1	1.8/1	Old data.
(30) Erikub 6017 9°10′N, 170°00′E.	5 x 16	74	30	22	40	1500	3	1.9/1	Scattered soundings.
(31) Aur 6014 8°20′N, 171°05′E.	5 x 16	72	48	28	38	1500	1	1.9/1	Discussed in text.
(32) Ailuk 6022 10°20′N, 169°55′E.	4½ x 15	61	34	25	39	1500	3	1.6/1	Steep inboard.
(33) Ujae 5428 9°02′N, 165°39′E.	5 x 22	57			30	1500	2	1.9/1	No soundings.
(34) Rongerik 6026 11°20′N, 167°27′E.	9 x 10	48	30	22	27.5	1300	2	1.8/1	Gentle inboard slope.
(35) Ailinginae 6026 11°09′N, 166°30′E.	3 x 14	36	17	15	33	1800	1	1.1/1	Soundings only around pass on west side.
(36) Taka 6023 11°10′N, 169°38′E.	5 x 8½	33	29	21	24	2000	1	1.4/1	Gentle inboard slope flat.

TABLE 2—*Con'td.*

Number, Name, Chart, and Co-ordinates	Maximum Dimensions (naut. mi.)	Lagoon Area (sq. mi.)	Maximum Depth (fms.)	Average Depth (fms.)	Reef Length (naut. mi.)	Reef Width (feet)	No. Passes	Lagoon Area/ Reef Length Ratio	Remarks
(37) Ebon 5429 3°38′N, 168°43′E.	7 mi. dia	32	21		21	1200	1	1.5/1	Soundings only around pass.
(38) Wotho 5427 10°08′N, 165°58′E.	5 x 12	30	23	21	27	1500	3	1.1/1	Only 4 soundings.
(39) Pokaakku 6024 14°38′N, 168°58′E.	3 x 10	28	8	7	28	1200	0	1/1	Gentle inboard. Many coral heads.
(40) Ujelang 6035 9°50′N, 160°53′E.	2 x 12	23	28	20	27	1500	0	.9/1	Gentle inboard slope.
(41) Utirik 6023 11°15′N, 169°38′E.	3½ x 8	22	27	22	23	1200	0	1/1	
(42) Bikar 6024 12°15′N, 170°06′E.	3½ x 6½	14	13	10	16	1000	0	.9/1	Gentle inboard. Many coral heads.
(43) Lae 6026 8°56′N, 166°14′E.	2½ x 4	5.7	36	27	9.5	1200	0	.6/1	Soundings only along south half.
(44) Namorik 5429 5°37′N, 168°07′E.	2 x 3¾	2.2			10	2100	0	.2/1	No soundings.
(45) Narik 6001 172°09′E, 5°55′N.	1 x 4	1.5			8	1000	0	.19/1	2 mi. SE. of Mili; connected by causeway at 4–5 fathoms.

172°09′E, 5°55′N.									way at 4–5 fathoms.

Lagoonless Coral Islands

(46) Jemo 5413 10°06′N, 169°30′E.	¼ x 4								Discussed in text.
(47) Mejit 5413 10°17′N, 170°52′E.	¼ x 1½								
(48) Kili 5414 5°39′N, 169°07′E.	¼ x 1½								
(49) Lib 5428 8°19′N, 167°24′E.	¾ x 1								Pond 450 yds. x 530 yds.
(50) Jabwot 6011, 5428 7°44′N, 168°59′E.	1500 feet by 4500 feet								

Banks

(51) Keats Bank 528 5°53′N, 173°29′E.									One sounding 8 fathoms.

If subsidence of the larger atolls and banks has been of the above order of magnitude, reef growth should have largely smoothed or obscured irregular submarine topography, and slopes should be relatively uniform to those depths. Further, small atolls or banks should be welded to close-lying large units by the sheathlike coral growth, and atolls separated by shallow saddles should be connected by coral causeways, or, at least, coral piers should finger out over the submarine ridge. Several examples are cited in which these theoretical reflections are entirely invalidated.

Maloelap (19), 281 square miles, and Aur (31), 72 square miles lie en echelon on the Radak trend, and, although both are irregular in shape, the major axes parallel the chain. In spite of the disparity in size, reef widths, reef development, and pass distribution are similar. The lagoon floor of Aur, however, dips southward from 20 fathoms to over 40. Although this anomaly confirms no theory, it demonstrates the inefficacy of detrital filling and leveling.

Narik (45), a small atoll 1 by 4 miles, lies 2 miles southeast of Mili (23). The two are connected by a causeway that parallels the trend and is drowned from 4 to 5 fathoms. This is one of three such examples in the three groups.

The five lagoonless coral islands in the group are all small. Lib (49) has a pond approximately 500 yards in diameter, probably a lagoon remnant. Jemo Island (46) is unusual because it has a reef that extends eastward about 4 miles. This could be a coral pier.

CAROLINE ISLANDS

GENERAL STATEMENT

With its 37 atolls, 34 known banks, 11 lagoonless coral islands, 2 uplifted phosphate islands, and 5 volcanic islands, the Caroline group presents more anomalies, as well as more definitive data, than any other group in the western Pacific. Most of the islands and banks lie in a belt 250 miles wide and 1900 miles long, from 4° to 10° North Lat. and from 132° to 163° East Long. The bathyspheric character changes greatly from west to east (Pl. 1): Palau and Yap have well-defined, though small, trenches on their southeast flanks; the west-central Carolines lie on a broad rise, the site of the majority of the banks; from Truk southeastward a short chain of atolls meets the broad nose which extends north from the Solomons; from Namonuito to Kusaie, 800 miles, the atolls and volcanic islands rise abruptly from the depths to form a gently curving arc. In spite of this diversity, with only a few notable exceptions, the reef relationships are remarkably uniform.

Truk, Palau, Ponape, Yap, Woleai, and Satawan were among the strongest enemy bases in the mandate. After their interdiction, the southern reef islands of the Palau group were stormed, and Ulithi and Ngulu atolls were occupied in September 1944.

CAROLINE ATOLLS

Figure 6 shows the 37 atolls scattered throughout the group. They vary in size from Namonuito (52) with a lagoon area of 570 square miles to Pingelap (88) with less than 1 square mile. Reef development is normal and uniform except for the

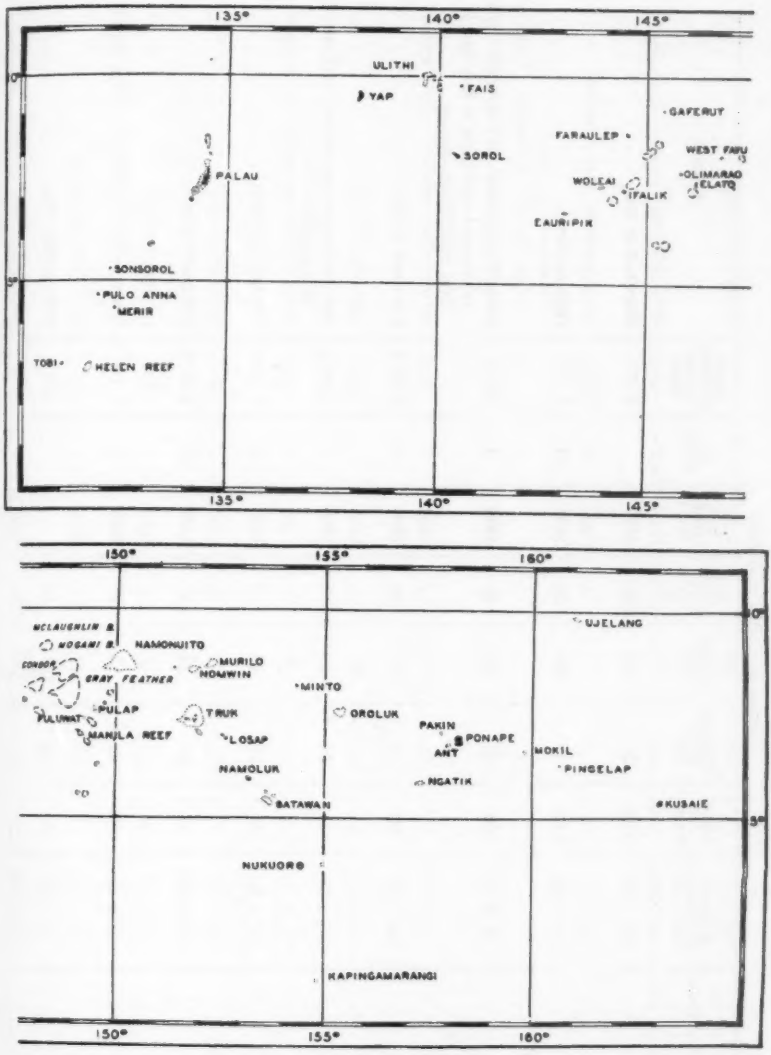


FIGURE 6.—*Caroline Islands*

bank area between Truk and Ulithi, where the atolls exhibit wide and numerous passes as well as long sections of drowned reef. In contrast with the Gilberts and Marshalls, shapes are irregular with no evidence of regional alignment.

Although the greatest lagoon depths are usually in the central areas, the reef walls are generally steep and do not grade into the lagoon floors. Exceptions are found in Oroluk (53), Nomwin (58), and Murilo (55) which are high in the central area.

TABLE 3.—*Atolls—Carolines*

Number, Name, Chart, and Co-ordinates	Maximum Dimensions (naut. mi.)	Lagoon Area (sq. mi.)	Maximum Depth (fms.)	Average Depth (fms.)	Reef Length (naut. mi.)	Reef Width (feet)	No. Passes	Lagoon Area/Reef Length Ratio	Remarks
(52) Namonuito 12018 8°24′N, 150°2′E.	28 x 46	570	51	30	122	2100		5.2/1	Discussed in text.
(53) Oroluk 6043 7°35′N, 155°18′E.	14 x 18	120	41	28	50	1400	11	2.2/1	High in center.
(54) Satawan 6044 5°24′N, 153°36′E.	8 x 18	104	42	29	45	1800	2	2.3/1	Inboard slope less steep on east. No evidence of coral piers to Lukunor or Etal, 5 and 4 miles distant.
(55) Murilo 6052 8°41′N, 152°12′E.	10½ x 21	103	29	22	50	1800	6	2.06/1	Discussed in text.
(56) Ngulu 6058 8°28′N, 137°29′E.	13½ x 21	101	46	23	54	1800	6	1.86/1	Reef submerged on east to 7 fathoms—16 passages.
(57) Ulithi 6055 9°56′N, 139°40′E.	14 x 19	85.5	27	19	56	1800	7	1.5/1	Discussed in text.
(58) Nomwin 6052 8°31′N, 151°47′E.	11½ x 14½	83.5	29	23	37	1800	4	2.25/1	Discussed in text.
(59) Helen Reef 6072 2°55′N, 131°46′E.	5 x 13	30	34	25	27	2400	1	1.1/1	Deep tortuous passage. Level lagoon floor.
(60) Manila Reef 5417 6°55′N, 149°10′E.	5 x 29	30	24	16N 21S	46			.65/1	Discussed in text.

(60) Manila Reef 5417 6°55′N, 149°10′E.	5 x 29	30	24	10N 21S	46				
(61) Ngatik 6108 5°50′N, 157°17′E.	5 x 11½	25	87	63	25	1500	1	1/1	Discussed in text.
(62) Kuop 6046 7°4′N, 151°55′E.	4 x 11½	24	34	23	27	2500	1	1/1	Discussed with Truk.
(63) Ant 6039 6°48′N, 157°58′E.	4½ x 6½	20	35	27	21	1800	1	.95/1	Discussed in text.
(64) Kapingamarangi 6042 1°4′N, 154°45′E.	5 x 6	15.5	43	32	17	1600	1	.9/1	Discussed in text.
(65) Lukunor 6044 5°31′N, 153°46′E.	4 x 7	15	34	22	17	1500	1	.9/1	Inboard slope not as steep as Satawan. Also 10 fathoms shallower.
(66) Zohhoiiyoru 6055 9°53′N, 139°57′E.	3½ x 12	15	30 ends 6 mid.	21	27	1800		.55/1	Discussed in text.
(67) Losap 5424 6°53′N, 152°42′E.	2 x 2½	10.5	18	16	15	1400	2	.7/1	Incompletely sounded. Two shallow boat passages.
(68) Pulap 5425 7°35′N, 149°25′E.	3 x 6½	10	22	17	16	1400	2	.62/1	East and southwest sides drowned; reef depth averages 6 fathoms. Deeper passages on SW. side.
(69) Minto Reef 5416 8°9′N, 154°17′E.	4½ x 5	9.5			14	1500	0	.68/1	No reef islands. No soundings.
(70) Lamotrek 6042 7°30′N, 146°20′E.	3½ x 8	9	29	23	18	1500	6	.5/1	Steep reef wall.
(71) Nukuoro 6042 3°51′N, 154°58′E.	3½ x 4	7.5	50	46	12	1200	1	.65/1	Discussed in text.

Except for Ngatik (61) and Nukuoro (71), with maximum depths of 87 and 59 fathoms, the lagoons are less than 50 fathoms; the smaller atolls are generally shallower.

Reef widths are remarkably uniform, and most average from 1500 to 1800 feet; again, there is no such variation in windward and leeward widths in the Carolines as in the Gilberts. In fact, Ulithi (57), Pulap (68), Ngulu (56), and Zohhoiiyoru (66) have the greatest development on the northwest, a relationship suggestive of eddy-current influence. The number of passes, moreover, cannot be correlated with reef width, lagoon depth, atoll size, or shape. Helen Reef (59), the southwesternmost atoll in the group and somewhat anomalous, averages 2400 feet wide and, although it is well developed with only one narrow passage, lies almost entirely underwater at high tide.

Elato (North) (81) and Elato (South) (84), both small atolls, have average depths of 13 and 10 fathoms, respectively, and are connected by a narrow bank a mile long that lies at 11 fathoms. This relationship suggests that vertical coral growth from very small or narrow platforms in the open sea is difficult or inhibited. Since the atoll reefs do not finger out over the bank, however, subsidence is disfavored.

Woleai (72), about half way between Truk and Palau, is roughly the shape of an 8 with long sections of drowned reef on the southern side. The eastern portion, considerably smaller, averages 17 fathoms as compared with the western 25, a fact indicating lagoon filling or tilting.

Kapingamarangi is apparently tilted to the northeast. The inboard slopes from the south and west sides are gentle, while the northeast reef wall is normal.

Manila Reef[2] (60) (Pl. 2), is 29 miles long and is made up of two atolls separated by a passage 90 fathoms deep and 2 miles wide. Except for Pulusuk Island, on the southern tip of the south atoll, the reef is submerged from 3 to 10 fathoms; the few soundings in the lagoon areas are from 14 to 24 fathoms. Manila Reef exhibits another good example of coral causeways and piers. It is conjectural as to whether this tenuity has resulted from coral growth on a subsiding ridge or from a stable ridge that barely reached sea level during the Pleistocene.

Nukuoro Atoll (71), between Satawan and Kapingamarangi, is oval-shaped, about 4 by 5 miles, and has one deep narrow passage on the south side. Reef width, development, and configuration are normal. The only unusual feature is a ring of coral heads which, with the oval reef, creates an excentric-circle effect. Figure 7, based on excellent data from H. O. Chart No. 6042, shows Nukuoro completely anomalous as far as normal atoll development is known. The inner reef wall drops precipitously to almost 20 fathoms where there is a level terrace 2000 to 5000 feet wide. The bases of the coral heads are located on the inner margin of this terrace which is marked by a steep scarp about 50 fathoms high, the toe of which does not grade into the central lagoon floor. This section is over 2 miles in diameter, lies below 50 fathoms, and is remarkably level.

The origin of Nukuoro presents a problem not only of unusual interest but also of exceptional import. The level floor at 50 fathoms, the wide uniform terrace at

[2] A categorical differentiation between atoll, drowned atoll, reef, and bank is difficult. Here any drowned atoll, rimmed reef, or bank that reaches low-tide level, regardless of the percentage, is arbitrarily classified as an atoll.

20 fathoms, and well-developed reef indicate secondary reef growth on a normal atoll—a decidedly "two story" effect. Subsidence would require atoll formation on a sinking foundation followed by uplift with only a small amount of attendant erosion that greatly modified neither the reef nor the lagoon floor. With renewed sub-

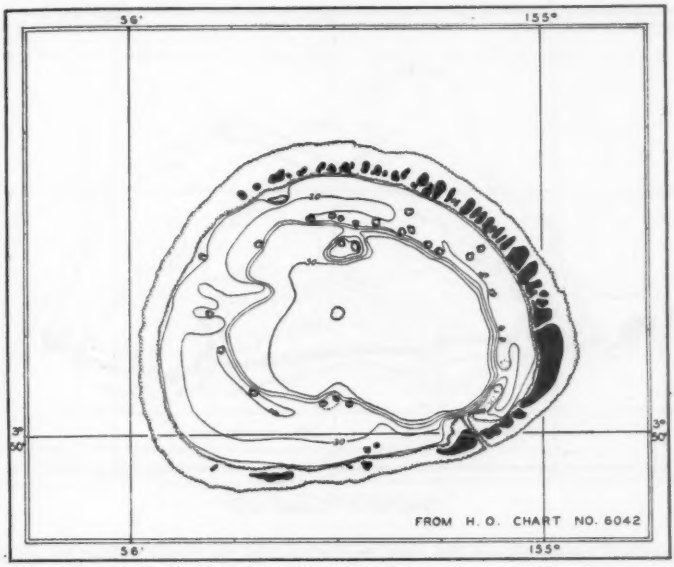


FIGURE 7.—*Nukoro atoll*

sidence, growth of the fringing reef that had developed around the uplifted atoll would result in the present relationships. The position of the coral heads is logically explained by coral growth on the lagoon margin of the old reef. The Glacial Control theory accounts for the abnormalities with somewhat greater ease because it does not demand subsidence, uplift, and subsidence. In this case, the first atoll could have been formed during an interglacial period. Subsidence, roughly commensurate with ocean lowering, followed during the Wisconsin stage. Reef growth was terminated, and slight erosional modification may have occurred. With the warming of the ocean a fringing reef developed around the old atoll, and, as the water returned, upward growth of this reef formed the present atoll. Since the reef volume of this atoll is approximately the same as other atolls of the Carolines and Marshalls, contemporaneity is indicated, and truncation is favored. The definitive factor, however, is the exceptionally flat lagoon floor which is separated from the level terrace by a near-vertical scarp; there is no evidence of filling of the lower lagoon level by detrital inwash. Thus, as Gardiner (1930, p. 146) generalized, the supply of coral detritus is insufficient to permit maintenance of a relatively constant lagoon depth as well as a level floor, two requisite factors for the acceptance of atoll formation by subsidence.

Ngatik Atoll (61) lies at 5°50′ North Lat., 157°17′ East Long., approximately 90

miles southwest of Ponape. The atoll is a low triangle 11 miles wide and, as far as known, is the deepest and has the steepest flank slope of any in the western Pacific. Although the north half, unfortunately, has not been sounded, the south half has been carefully charted. There are nine soundings over 80 fathoms, the deepest 87

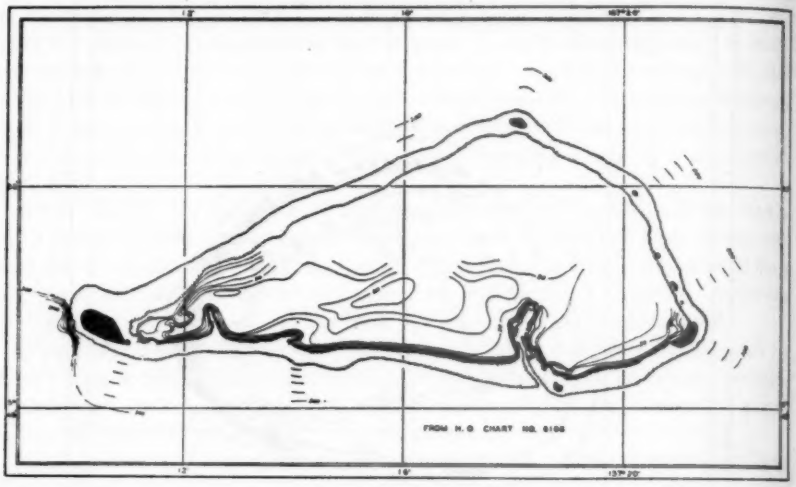


FIGURE 8.—*Ngatik atoll*

(522 feet). Figure 8 shows the steep reef walls, the flat lagoon floor, much of which is below 60 fathoms, the deep tortuous passage, and the apparent tilt southward. The submarine slopes are normal except off the west tip where soundings over 900 fathoms within 400 yards of the seaward reef margin indicate the declivity to approximate 75°. Since this is much higher than the angle of volcanics or coral-detritus repose or known reef ingrowth, a submarine landslide or fault of considerable magnitude is indicated.

In spite of the fact that Ngatik is extraordinary, it presents no evidence that strongly condemns or supports a particular theory of origin. Although the excessive depth is perhaps expectable under Darwin's theory, the Glacial Control theory is not impaired because the abnormal submarine slope can be readily utilized to support an isolated example of instability. It is noteworthy, however, that the reef development is vigorous and uniform with only one narrow passage and that lagoon filling has failed to maintain the level supposed by Davis.

Ulithi Atoll (57) is about 400 miles southwest of Guam Island and 100 miles northeast of Yap Island. Zohhoiiyoru Bank (66) is to the east, and Falalop Island (132) and Pau-Losiep Islands (123) lie on a submarine trend that joins Ulithi and Zohhoiiyoru. Although the reef islands on Ulithi are very low and narrow, reef development is normal except for the submerged portions of the eastern section and the wide reef segment on the northwest. The lagoon floor is very level, at approximately 20 fathoms. Zohhoiiyoru Bank is shaped like an 8, and the reef, all except a short

section on the north end which is at sea level, lies under 7–10 fathoms. The north and south lagoon sections reach depths of 30 fathoms, while the constriction gradually shallows to 10 fathoms. Since the height of the drowned rim of the north and south sections is approximately the same as the normal rim surrounding Ulithi, truncation

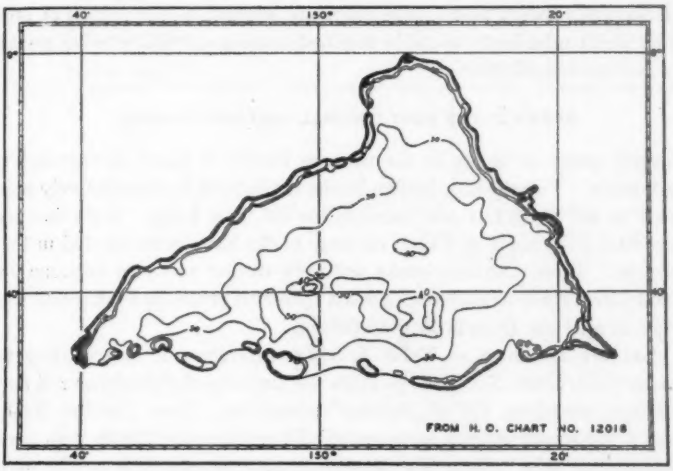


FIGURE 9.—*Namonuito atoll*

is somewhat favored because detrital inwash should not fill Ulithi and Zohhoiiyoru to the same level when the lagoon area/reef length ratios are 1.5/1 and .55/1. Other factors that support truncation are the variation in shallow submarine slopes and the absence of any coral causeways or piers along the trend, even though Ulithi and Falalop are separated by a channel less than a mile wide and 100 fathoms deep.

Nomwin (58) and Murilo (55) atolls lie about 75 miles north of Truk. Both atolls are on the same trend and are separated by a saddle approximately 6 miles wide and 500 fathoms deep. Although they are normal from all surface indications, two unusual features are manifested: (1) There is a relatively level terrace or bench approximately a mile wide that extends northeastward from the northeast tip of Nomwin about 1½ miles toward Murilo. Since lagoon filling over the bank is precluded and since the bank lies at approximately 30 fathoms, but little deeper than the lagoon, truncation easily explains the relationship, while subsidence is inadequate. (2) The lagoons have central sections that are about 10 fathoms shallower than the lagoon floor immediately contiguous to the steep reef wall. Again the efficacy of lagoon filling is condemned.

Namonuito Atoll (52), the largest in the Caroline Islands, is triangular-shaped with a lagoon area of 570 square miles. It is 150 miles northwest of Truk at the northeast limits of the bank area which is discussed later. Reef islands are found only on the southwest, southeast, and northern apices (Fig. 9). Although the remainder is drowned, a well-developed reef perimeter is found on the northwest and northeast

sides at depths less than 10 fathoms. On the south side, however, long sections are in a true bank condition with no evidence of rim-reef growth, a relationship that exhibits an abrupt break from the level lagoon floor to the steep declivity that descends to the depths. In spite of this semidrowned state, the lagoon depth is not excessive, a fact indicative of incipient or inhibited reef growth on a truncated foundation. If Darwin's theory and lagoon filling are applied, a long period of stillstand followed by slight subsidence would be required because detrital leveling would quite probably be even less effective.

BANKS IN THE WEST-CENTRAL CAROLINE ISLANDS

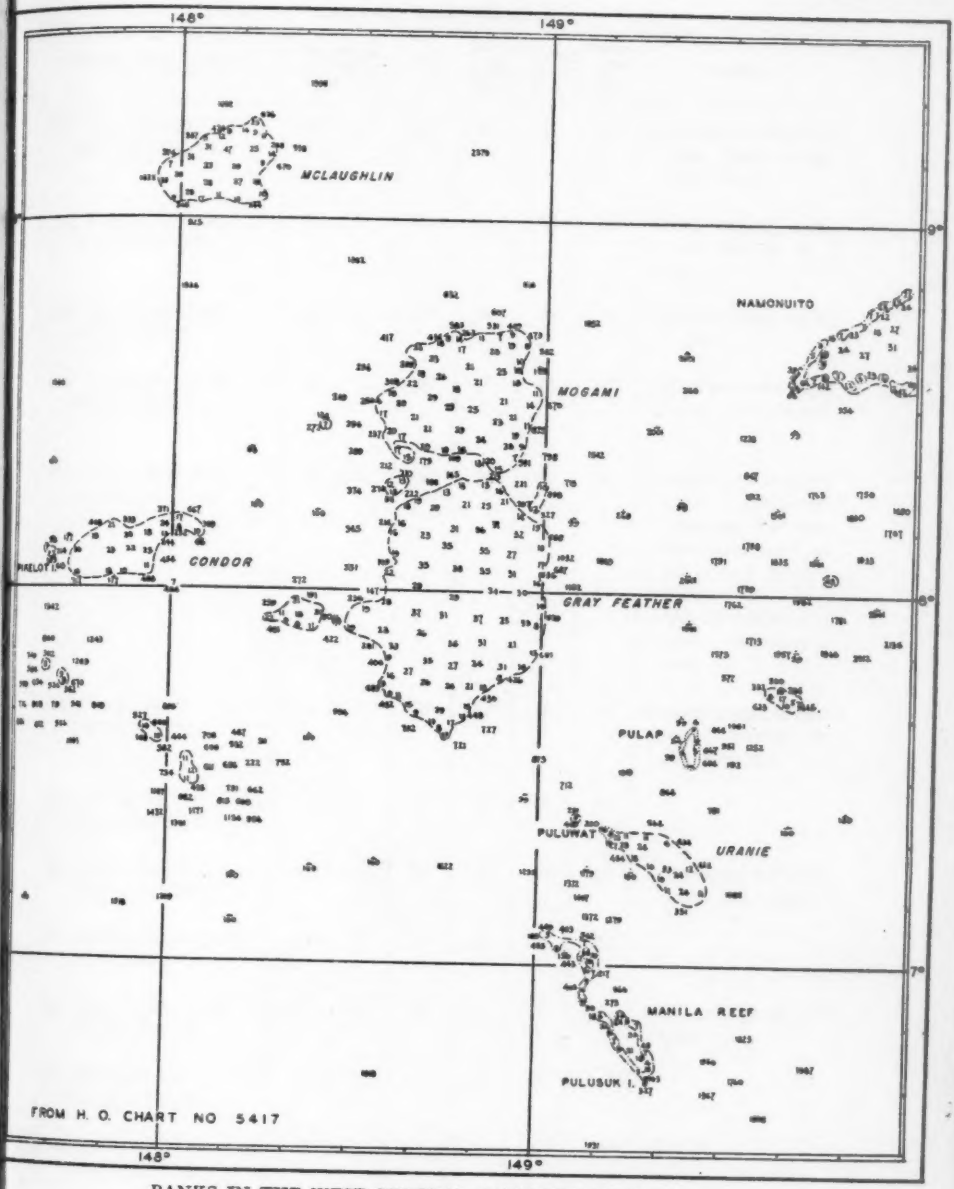
The largest group of banks in the western Pacific is found in the west-central Caroline Islands. Twenty-nine known banks are located in the relatively restricted area from 5° to 10° North Lat. and from 144° to 150° East Long. With the exception of Velasco Reef (93), north of Palau, no large banks have been charted in the three island groups. These Caroline banks are very similar to those between the Fiji Islands and Ellice atolls which are discussed by Davis (1928, p. 84–85) and which he collectively termed the Darwin Hernatopelago.

Bank data are tabulated in Table 4, where arrangement is according to size. Plate 2, after H.O. Chart No. 5417, includes the major banks which, as will be noted, have sufficient soundings for satisfactory delineation. Gray Feather Bank (89), the largest, is 885 square miles, approximately 220 square miles larger than the lagoon of Kwajalein Atoll (17). There is a well-developed rim, especially on the south side where the depths are only 8 fathoms as compared to an average of 32 fathoms in the central area (Pl. 2). Mogami Bank (90), the second largest and about 9 fathoms shallower, lies north of Gray Feather and is separated from it by a channel a mile wide and 213 fathoms deep at the narrowest point. Mogami also has a well-developed rim on the east and north sides. Shin Matsuye (98), Koyo (110), and three unnamed banks complete this group. All five are of normal depth, lie within a few miles of each other, and none are separated by channels over 300 fathoms deep.

McLaughlin Bank (91) has a conspicuous rim with a minimum depth of 7 fathoms. The central area has a maximum depth of 47 fathoms, 1 fathom less than the deepest recorded over Caroline Banks. Condor (92), as well as several smaller banks, also has soundings indicative of rim structures.

Puluwat (86) and Ngaruangl (76) are faros located on banks. Although hydrographic charts show the Puluwat Islands as a small atoll on the northwest tip of Uranie Bank (94), aerial photographs indicate that the bank extends considerably farther west. Depths are not so great in the lagoon as over the bank, probably because of reef encroachment and detrital filling. Ngaruangl Reef is a small shallow atoll on the south end of Velasco Reef (93), another large drowned atoll. Ngaruangl's lagoon is slightly shallower than the adjacent drowned reef rim. Both Puluwat and Ngaruangl apparently formed from reef growth around one of the reef islands of the drowned atoll. Pikelot Island (108) is probably located on the west edge of a small incompletely surveyed bank.

There seems little doubt that most of these banks are drowned atolls or incipient reefs on an antecedent platform. Although the problems of reef growth may fall



BANKS IN THE WEST-CENTRAL CAROLINE ISLANDS

TABLE 4.—*Banks—Carolines*

Number, Name, Chart and Co-ordinates	Maximum Dimensions (naut. mi.)	Area (sq. mi.)	Maximum Depth (fms.)	Average Depth (fms.)	Perimeter (naut. mi.)	Remarks
(89) Gray Feather 5417 8°N, 148°45′E.	32 x 43	885	38	32	120	Perimeter average 15 fms. South section up to 8 fms.
(90) Mogami Bank 5417 8°35′N, 148°45′E.	23 x 27	425	29	23	93	Perimeter slightly high; east side up to 7 fms.
(91) McLaughlin 5417 9°7′N, 148°5′E.	14 x 20	177	47	30	53	Perimeter high; up to 9 fms.
(92) Condor Reef 5417 8°7′N, 147°50′E.	9 x 24	142	30	23	52	Part of perimeter high; up to 8 fms. on east end.
(93) Velasco Reef 6074 8°20′N, 134°37′E.	8 x 20	118	29	23	46	Apparently a drowned atoll. Perimeter sounding 6–11 fms. Ngaruangl Reef on south end, 2 by 3 miles, 3 fms. deep, slightly submerged atoll. Discussed in text.
(94) Uranie 5417 7°15′N, 149°15′E.	6 x 18	88	33	25	40	Perimeter high; up to 6 fms. Puluwat on northwest end.
(95) Tarang 5417 8°25′N, 145°15′E.	4 x 14	44	25	20	27	
(96) Gamen Reef 5417 7°27′N, 144°40′E.	5 x 14(?)	44	12	10?	28	Incompletely surveyed —only 3 soundings.
(97) Earl Dalhousie 5417 8°7′N, 144°55′E.	8 x 8	36	32	21	20	
(98) Shin Matsuye 5417 7°55′N, 148°20′E.	5 x 10	35	22	20	20	South rim high; up to 8 fms.
(99) Hitchfield 5417 7°41′N, 149°40′E.	3 x 6	17	17	10	13?	
(100) Condor 5417 7°29′N, 148°5′E.	3 x 6	17	12	11	13?	3 soundings.
(101) Helen Shoal 5417 5°35′N, 149°27′E.	2 x 15	7	21	17	28	5 fathoms on east and west ends.

TABLE 4—*Cont'd.*

Number, Name, Chart and Co-ordinates	Maximum Dimensions (naut. mi.)	Area (sq. mi.)	Maximum Depth (fms.)	Average Depth (fms.)	Perimeter (naut. mi.)	Remarks
(102) Lady Elgin 5417 6°18′N, 149°27′E.	2½ x 6	7	11	7	7	4 soundings.
(103) Oraitilipu 5417 8°9′N, 147°15′E.	3 x 5	7	20	14	12?	3 soundings.
(104) Unnamed 6073 6°56′N, 134°12′E.	1 x 2½	2	23	12		Apparently a low seamount on the Palau arc but little truncated.
(105) Ianthe Shoal 5417 5°58′N, 145°25′E.			7	7		5 soundings—outline poorly defined.
(106) Ulloa Reef 5417 7°2′N, 144°12′E.			10			1 sounding.
(107) Orairuguron 5417 7°15′N, 146°7′E.			21			1 sounding.
(108) Tarang Reef 5417 7°45′N, 147°42′E.			9	8		2 soundings.
(109) Pikelot 5417, 5425 8°6′N, 147°38′E.			7			Pikelot I. on bank 7 fms. deep—2 soundings.
(110) Matsuye 5417 8°1′N, 148°1′E.			7			1 sounding.
(111) Koyo 5417 8°27′N, 148°24′E.			7			1 sounding.
(112) Hunter 5590 9°50′N, 138°20′E.			12			1 sounding.
(113) Unnamed 5417 8°17′N, 148°36′E.			15	13		3 soundings.
(114) Unnamed 5417 7°36′N, 142°58′E.			10	10		2 soundings.
(115) Unnamed 5417 8°15′N, 148°59′E.			12	11		2 soundings.
(116) Unnamed 5417 8°11′N, 145°5′E.				14		1 sounding.
(117) Unnamed 5417 7°45′N, 145°54′E.				15		1 sounding.

TABLE 4—*Concl'd*

Number, Name, Chart and Co-ordinates	Maximum Dimensions (naut. mi.)	Area (sq. mi.)	Maximum Depth (fms.)	Average Depth (fms.)	Perimeter (naut. mi.)	Remarks
(118) Unnamed 5417 7°47′N, 147°38′E.				8		1 sounding.
(119) Unnamed 5590 10°40′N, 140°7′E.				19		1 sounding.
(120) Unnamed 5417 7°24′N, 149°6′E.				8		1 sounding.
(121) Unnamed 5417 8°3′N, 149°47′E.				48		1 sounding.
(122) Unnamed 5590 6°2′N, 133°20′E.				13		1 sounding.

argely within the biologist's province, the abnormalities found in this area certainly affect the geologist's conception of reef disposition. Why should an area of dormant reefs be surrounded by one of active growth when the physical conditions are apparently the same?

The bank area is bounded on the east by the excellent reef growth at Truk, Nomwin, Murilo, and Satawan, on the south by the reefs of the Bismarck Archipelago, on the north by the Marianas, and on the west by the atolls of Ulithi and Ngulu and by Yap Island. Within this definitive boundary are the poorly developed atolls of Namonuito (52), Pulap (68), and Manila Reef (60), which are perhaps better called drowned atolls, the small atolls of Lamotrek (70), Elato (81 and 84), Olimarao (78), and the banks. There is no obvious reason why these banks are not favorable sites for vigorous reef growth. They lie at approximately the same depth as the lagoon floors of normal atolls; none are excessively deep. They also lie within the belt traversed by the northeast trades and doldrums, as do the Carolines and sections of the Marshalls and Gilberts. As far as known there are no variations in salinity, turbidity, temperature, ecology, or climatic factors that should prove deleterious. The structural position is anomalous, however, because the banks are located on the broad rise found in the west-central Carolines. Since depths of over 1000 fathoms still remain, this fact can hardly be more than fortuitous.

The only physical variations to which appeal can be made are current set and drift in the bank area from May to September and abnormal diurnal tidal ranges. Although current phenomena are incompletely known in the western Pacific, weak eddy currents occur between the north equatorial current and the counter equatorial current. These eddy currents set from north to south with velocities of about one-third knot and spiral counter-clockwise in the bank area. Therefore, during the summer the food supply may be insufficient for active reef growth.

The banks also lie in one of the nodal-point areas of the Pacific. Here the diurnal tide range averages about 1½ feet, and during the moon's quarters there is but one

high and one low every 24 hours. It is not known if such conditions affect coral growth.

Davis (1928, p. 484) in referring to the Darwin Hermatopelago summarized theories of bank origin with,

> "According to the Glacial control theory the submerged rims represent unsuccessful Post-glacial reef upgrowths over abraded platforms; according to Darwin's theory, they represent sea level atoll reefs which have been submerged by a broad and astonishingly even sinking of the sea floor hereabouts".

Two facts prove difficult to explain by the subsidence theory. Why have they sunk, regardless of size, less than 50 fathoms and then stopped? Since large seamounts would have to sink thousands of feet to reach their present positions by subsidence, why should Gray Feather and Mogami, as well as others, be separated by a shallow channel with rim reef growth on either side? The concept of lagoon filling and leveling also seems inadequate to account for a level floor on banks of this size without requiring a relatively long stillstand or very slow subsidence with active reef growth followed by dormancy. The theory of incipient reef growth on antecedent platforms is not supported by known current anomalies. Although eddy currents of the summer may not have afforded locomotion necessary for effective colonization, during the winter the north equatorial current was probably of similar set and drift as in the eastern Carolines and Gilberts. Relative stability coupled with truncation and followed by inhibited reef growth adequately accounts for all the relationships.

LAGOONLESS CORAL ISLANDS

The eleven sea-level coral islands are located in the central and western Carolines: East Fayu and Nama within 100 miles of Truk, Satawal and Gaferut in the bank section, Falalop and Pau-Losiep east of Ulithi, and Sonsorall, Fana, Pulo Anna, Merir, and Tobi between Palau and Helen Reef. Insofar as known, all are coral caps on submarine volcanic seamounts.

These islands are all very small: East Fayu (123), the largest not on a trend, is 1 by 2 miles; Gaferut (133), the smallest, is a quarter of a mile by half a mile. East Fayu and Gaferut have small ponds. The remaining nine, if once atolls, have been completely filled; reported phosphate deposits on Tobi indicate at least one because phosphate is frequently associated with lagoon filling in the western Pacific, evidence that lagoons at sea level are filled in slowly rather than enlarged by solution as Murray (1880) contended.

Davis (1928, p. 513) considered small atolls and coral islands significantly in favor of Darwin's theory because he deemed it more logical that these should result from coral upgrowth and ingrowth on subsiding foundations than that numerous seamounts should barely reach sea level. Gaferut, with the steepest submarine slopes, seemingly substantiates his observation because the slopes approach 45° to depths of 400 fathoms, considerably higher than those found on larger atolls or expected from submarine volcanics. This evidence, however, is not completely diagnostic because subsidence could have been pre-Pleistocene, and the islands could represent recent coral growth on truncated coral foundations. Nonetheless, it is worthy of note that these abnormal slopes are the best indication in the Carolines that coral may grow

TABLE 5.—*Lagoonless Coral Islands—Carolines*

Number, Name, Chart and Co-ordinates	Maximum Dimensions (naut. mi.)	Remarks
(123) Pau-Losiep 6055 9°56′N, 139°50′E.	1 x 3	On trend between Ulithi and Zohhoiiyoru.
(124) East Fayu 5425 8°34′N, 151°22′E.	1 x 2	Very small fresh-water lake in center.
(125) Merir 5426 4°20′N, 132°19′E.	¾ x 2¼	
(126) Sonsoroll 5426 5°20′N, 132°13′E.	¾ x 1½	Sonsoroll lies 4000 feet south of Fana with a channel depth of 205 fathoms. No coral piers.
(127) Tobi 5426 3°1′N, 131°11′E.	¾ x 1¼	SW. most island in Carolines. Reported phosphates.
(128) Satawal 5426 7°21′N, 147°2′E.	½ x 1½	Shallow reef extends eastward 3500 feet.
(129) Fana 5426 5°21′N, 132°13′E.	¾ x ¾	
(130) Nama 5424 7°N, 152°34′E.	½ x 1	Nama lies 8 miles northwest of Losap Atoll.
(131) Pulo Anna 5426 4°40′N, 131°58′E.	½ x ¾	
(132) Falalop 6055 10°2′N, 139°48′E.	½ x ¾	Lies off northeast tip of Ulithi.
(133) Gaferut 6042 9°14′N, 145°23′E.	½ x ½	Small lagoon at northwest end.
UPLIFTED "PHOSPHATE" ISLANDS		
(134) Fais 5426 9°46′N, 140°31′E.	¾ x 1¼	Discussed in text.
(135) Anguar 6073 6°55′N, 134°9′E.	2 x 2½	Discussed in text.

steeply from small foundations particularly in view of the paucity of coral causeways over shallow saddles.

Fais Island (134), 9°46′N Lat., 140°31′E. Long, and Anguar Island (135), 6°55′N. Lat., 140°31′E. Long., are uplifted and have phosphate deposits. It is conjectural as to whether or not they are raised atolls. Anguar has some evidence of rim structure, particularly to the northwest, and two small ponds. Fais is flat, all about 100

feet above sea level, and is bounded by steep cliffs. The underwater gradients, however, are abnormally low for some distance off shore which may indicate that wave action has removed the rim.

VOLCANIC ISLANDS IN THE CAROLINE GROUP

Fringing and barrier reefs surround the five volcanic islands in the Caroline group. The islands are spaced from the eastern to the western end of the Carolines and manifest diverse stages of topographic development and various reef relationships. Kusaie, a rugged island with a narrow fringing reef, is the youngest and lies at the eastern end; Ponape, the next youngest and the largest single volcanic island, is partially circumscribed by a fringing reef and partially by a barrier reef; Truk, the great almost-atoll, is in the central Carolines; Yap is a much eroded low-lying island surrounded by a fringing reef; and Palau, the westernmost, manifests phenomena related to instability. Thus, a relatively comprehensive evaluation of the manifold relationships between volcanic land masses and off-lying reefs is possible.

Kusaie Island is approximately 5 miles wide and reaches 2000 feet. The island is surrounded by a flat coastal band that averages half a mile in width. The fringing reef which circumscribes the island, although relatively narrow, is well developed in spite of Kusaie's youth (Fig. 10).

All spurs have been truncated; in fact the entire mountainous section is separated from the flat coastal lowland by abnormally steep slopes, some over 400 feet high. In profile, the mountain slope is sharply intersected by the steep declivity which is bounded by the flat lowland that slopes gently seaward to the reef margin. Such a relationship is obviously a result of wave erosion. The period of erosion, however, poses a considerable problem. If Davis' concept of inhibited reef growth on young or rising foundations is followed—a theory not entirely borne out by numerous sea-level reefs on young volcanic islands or by uplifted fringing reefs—erosion would be assumed prior to establishment of the fringing reef. If, however, growth is granted on young foundations, the cliffs and sea-level bench were cut during a period of reef dormancy. Although there are some relatively fresh-looking low cliffs on the south side, it is highly unlikely that the steep slopes 300 to 400 feet high could have formed in Pleistocene time.

Ponape is the largest island of the Senyavin Islands. It is a rugged volcanic island approximately 12 miles in diameter. Hobbs (1944, p. 265) has reported the rock as olivine basalt, very similar to that of Kusaie, Truk, and the Hawaiian group. The higher peaks are offset slightly to the southeast, the steeper-to side, and reach 2500 feet. Ridges that radiate from the central highland have been truncated, and instead of a stellate outline the perimeter is relatively circular, interrupted by a few shallow bays (Fig. 11).

As at Kusaie, there is abundant evidence of truncation. Although it may be argued that most of this wave action occurred before the island had been sufficiently reduced for active reef growth, as is probable at Kusaie, the more advanced erosional stage and the abrupt sea-level cliffs as far as 4 miles from the barrier reef indicate relatively recent erosion. While the major cliffs, such as Jokaj Rock which is about 900 feet high, result from differential resistance and erosion, the cliffs that surround

the low-lying lagoon islands are much more likely attributable to recent wave action.

Several interesting features are found on the southeast side of the island. South of Matalanim Harbor there is evidence of two wave-cut cliffs separated by a relatively narrow bench. This relationship, suggestive of uplift, finds the movement in

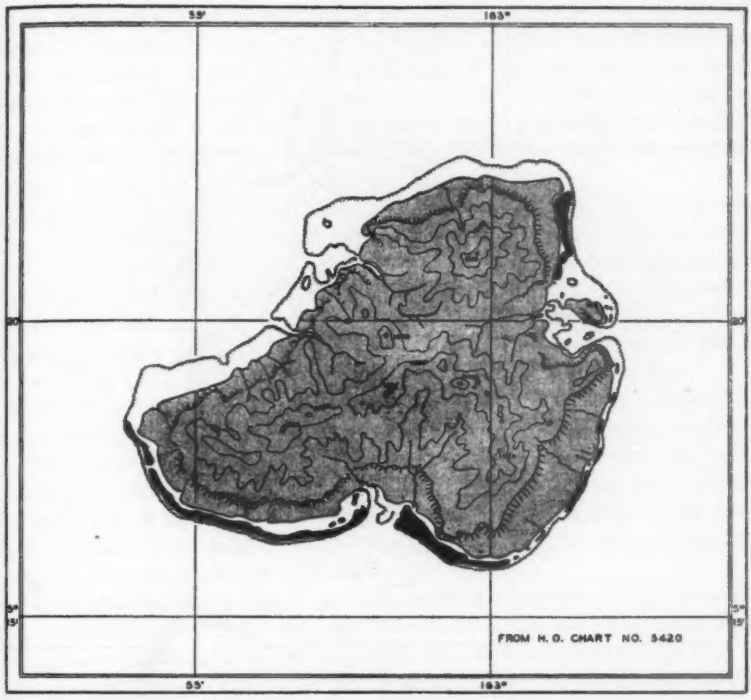


FIGURE 10.—*Kusaie Island*

the wrong direction, if subsidence is to explain the asymmetry of reef position and peak displacement. On the north side of Matalanim Harbor are the rim remnants of a small breached crater. Since the Chapaplap River, the largest on the island, flows through the crater, the fact that the crater floor is the same depth as the lagoon is difficult to explain unless the crater had been filled to a truncation plane. At the constricted harbor passage, inside the reef, a depth of 52 fathoms is reached, a result of valley erosion during a glacial stage or evidence of subsidence. Since, however, the passage is the same depth through the reef as the surrounding lagoon, the former explanation is somewhat more logical.

Reef disposition shows an asymmetry similar to the topography. On the southeast side there is a relatively narrow fringing reef which gradually draws away from the shore line until the protected fringing reef and the barrier reef are 5 miles apart on the north side of the island. The fringing reef width is approximately the same as the atoll reefs—evidence of contemporaneity—, and, although the lagoon area/reef-

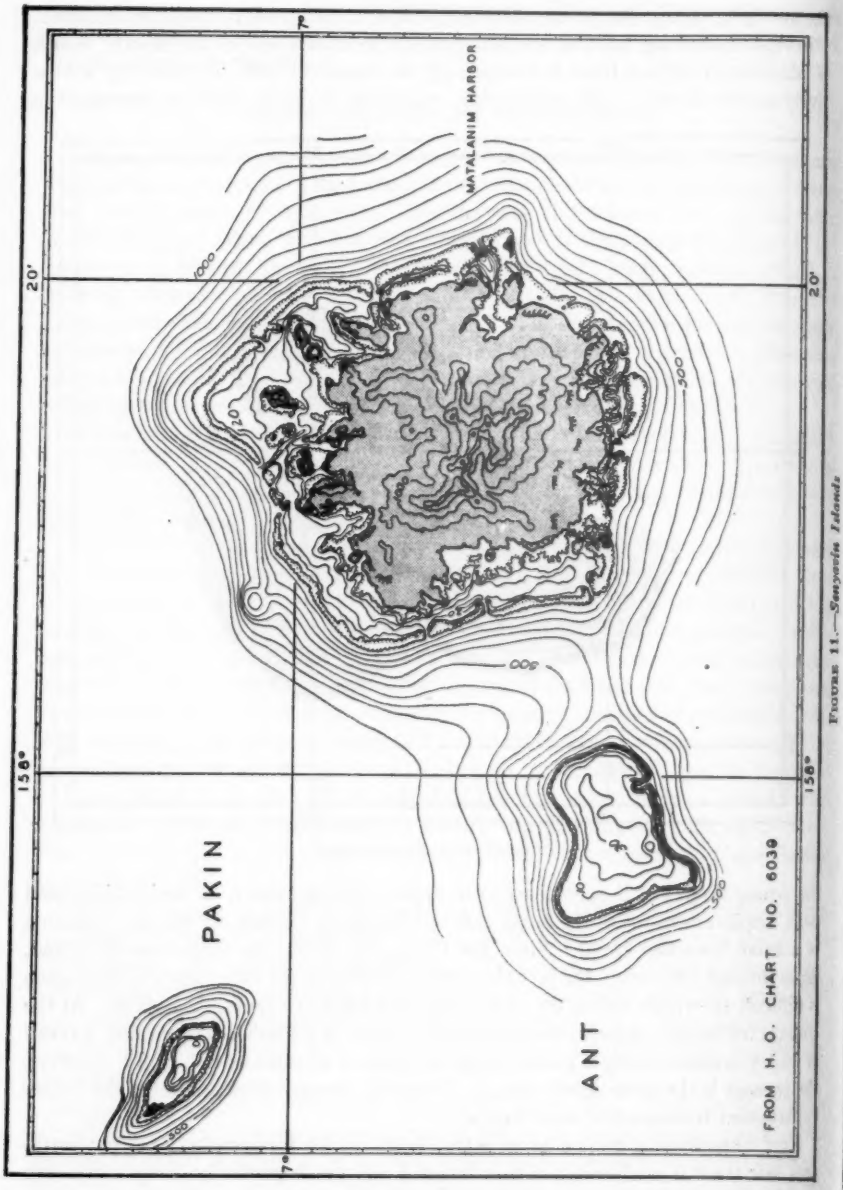


FIGURE 11.—*Senyavin Islands*

length ratios vary greatly around the island, lagoon depths are remarkably uniform—concrete evidence of the relatively minor amounts of detrital inwash.

Ant (63) and Pakin (75) atolls complete the Senyavin Islands. Ant lies about 6 miles west of Ponape and is separated from it by a submarine saddle less than 500 fathoms deep. Pakin is about 17 miles northwest of Ponape and is smaller than Ant. The lagoon depths of both atolls and Ponape are approximately the same, a relationship difficult for subsidence to explain, for it is illogical to assume that all three have sunk the same amount or that the reefs of Ant and Pakin could supply as much detritus as the reef and land mass of Ponape. Also, since reef widths of all three are similar, the ages should be similar, another factor easily explicable by truncation without recourse to special conditions. Last, the absence of coral piers between Ponape and Ant does not favor subsidence.

On the flanks of Ponape and Ant there is indication of a break in slope at 500 fathoms, a relationship also found at Eniwetok, Ulithi, and Murilo. This similarity in depth follows more readily if it is assumed that the upper slope resulted from a talus accumulation of coral detritus after truncation and subsequent reef growth. If, however, the break in slope was caused by reef growth and coral talus on sinking foundations, a similar amount of subsidence must be postulated for all islands, a highly specialized and unlikely case for this disparity of atoll and island sizes.

Truk, the finest almost-atoll in the Pacific, offers considerable data. Figure 12, based on a meticulous and exhaustive survey, shows reef, island, and lagoon relationships. The barrier reef is 114 miles long and surrounds a lagoon with maximum dimensions of approximately 34 by 38 miles. Within the lagoon are six relatively large volcanic islands and eight small ones. The volcanic island/lagoon area ratio is considerably less than 1 to 10. Two miles south of the reef, across a passage less than 400 fathoms deep, lies Kuop Atoll (62).

The lagoon and reef are normal. Average depth is approximately 28 fathoms; greatest recorded depth is 43 fathoms, not 58 as Davis (1928, p. 377) reported from German surveys. The degree of levelness of the floor is commensurate with that of atolls of comparable size. The barrier reef is approximately the same width as the atoll reefs in the Carolines and Marshalls; as usual, maximum width and fewest passes are on the windward side. The protected fringing reefs that surround the volcanic islands are of normal width.

The volcanic islands have been reduced to relatively insignificant size; Tol and Moen, the largest, are less than 5 miles long and have maximum elevations of only 1483 and 1214 feet. In spite of this stage of weathering and erosion, practically every volcanic island is rimmed on a portion of its perimeter by steep, although usually low, cliffs. The cliff symbols (Fig. 12) show these positions; some of the cliffs on Moen, Dublon, and Uman islands are well over 100 feet high. The east side of Tol Island shows exceptional development; these cliffs, however, are more logically considered a result of differential weathering because the topography indicates a dipping cap of resistant lava. The south side of the island has normal low wave-out scarps. Further substantiation of wave action is found in the complete absence of underwater spurs rising above the lagoon floor, as shown by large-scale charts.

FIGURE 11.—*Senyavin Islands*

FROM H. O. CHART NO. 6039

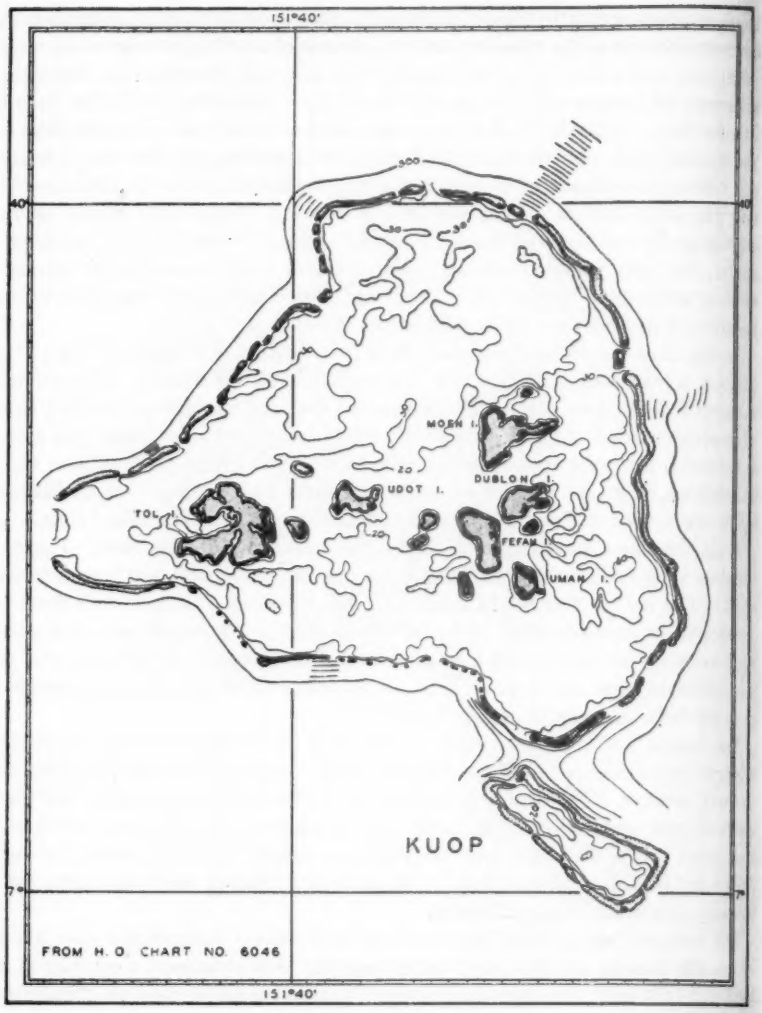


FIGURE 12.—*Truk Islands*

Kuop Atoll (62), 4 by 11 miles, has reefs slightly wider than those of Truk and a relatively uneven lagoon floor that averages about the same depth as the lagoon at Truk. There is no indication of a reef causeway across the shallow saddle.

The wave-cut cliffs, the absence of underwater spurs, the lack of pass notches, and the accordance of lagoon depths are hardly explicable by subsidence.

The four larger volcanic islands in the Yap group are Yap, Gagil-Tomil, Map, and Rumung. They are separated by narrow waterways, the result of slight negative

movement, and are surrounded by a fringing reef that averages a mile in width. Narrow lagoons or estuaries, some with through passages, lie within the reef (Fig. 13); maximum depth is 25 fathoms. The 7 by 17-mile triangular mass is bounded on the east and southeast by the Yap trough, previously described.

FIGURE 13.—*Yap Islands*

Yap is of special interest because it approaches the pre-Pleistocene aspects that Daly prescribed for Pacific seamounts. The land mass has been greatly subdued by weathering and erosion; maximum elevations on Yap island are less than 600 feet and on the other three less than 300 feet. Hobbs (1944, p. 244) has described the rock as of

"two widely different types, both greatly decomposed. One is an older augite andesite, now a red lateritic decomposition product which occupies the eastern half of the island complex; and this is in surface contact along a north-south medial line with a basic greenstone schist, in places talcose or actinolitic, which is the decomposition product of a black basalt."

In spite of this petrologic condition, a prominent truncated spur is found on Map Island, and cliffed shore lines on Rumung and Gagil-Tomil islands. These cliffs lie on the east and north sides, the windward approach during the northeast trades. Steep high cliffs are found on the Yap side of the passage between Yap and Gagil-Tomil as well as lower cliffs on the southeast and southwest flanks of Yap Island.

Although the trough indicates a region of tectonic instability, with any theory the greatly decomposed volcanics surrounded by a fringing reef rather than a barrier reef demand a long period of stillstand. Since the truncated spur and cliffed shore lines are hardly attributable to any factor except recent wave action, it must be concluded that Yap escaped complete truncation because erosion and decomposition had still not progressed sufficiently.

The Palau arc is about 100 miles long and (Fig. 14) includes from south to north: Angaur Island (135), an uplifted island with phosphate deposits; an unnamed bank (104); the Palau group; the small shallow atoll of Kayangel (74); and Ngaruangl Reef (76), the small shallow atoll on the south end of Velasco Reef (93). In the Palau group the southern islands are coral with conspicuous uplifted reefs that have been described by Semper (1881), Hobbs (1944, p. 248–249), and others; the central and north-central section includes the small islands of Korror, Malakal, Arakabesan, and Aurapuskekaru, part volcanic and part coral, and the large volcanic island of Babelthuap; reef-formed Kossol Passage rounds off the north end. The east flank of the arc dips steeply to the trough; most of the reefs off eastern Babelthuap are fringing. To the west slopes are gentler, and Babelthuap is protected by a barrier reef that flares to the southwest.

An abnormality is found in the maximum reef development to the west where the barrier reef is up to a mile in width; on the east the reefs are interrupted and maintain the average of the other Carolines. The lagoons of Palau and Kossol Passage and Velasco Reef are approximately the same depth with a maximum slightly over 30 fathoms. Kayangel and Ngaruangl are both abnormally shallow with maximum depths of 5½ and 5 fathoms. A well-defined lagoon channel, the only one in the three groups, in part over 10 fathoms deep, lies on the southwest side of Babelthuap and connects West Passage. The main lagoon at Palau also has an unusually large number of drowned coral heads.

Babelthuap, 9 by 24 miles, is composed "largely of a hypersthene and augite andesite lava with its corresponding volcanic sediments, a red tuff largely altered to laterite and interbedded with agglomerate and volcanic breccia" (Hobbs, 1944, p. 246). Bauxite is found on the northwest part of the island, and lignite deposits on the west side. The island has three ridges separated by low-lying valleys that parallel the major axis; the highest elevation is 794 feet. The easternmost ridge lies close to the coast; the shore line is cliffed in several sections. The west shore line also has several truncated spurs in the central section as well as some low cliffs. On the east side of the island there are stream terraces along several alluviated valleys. On the southwest side, 22 scarps of remarkably uniform height show the flows dipping westward, while a few scarps on the east indicate that the formations are flat lying.

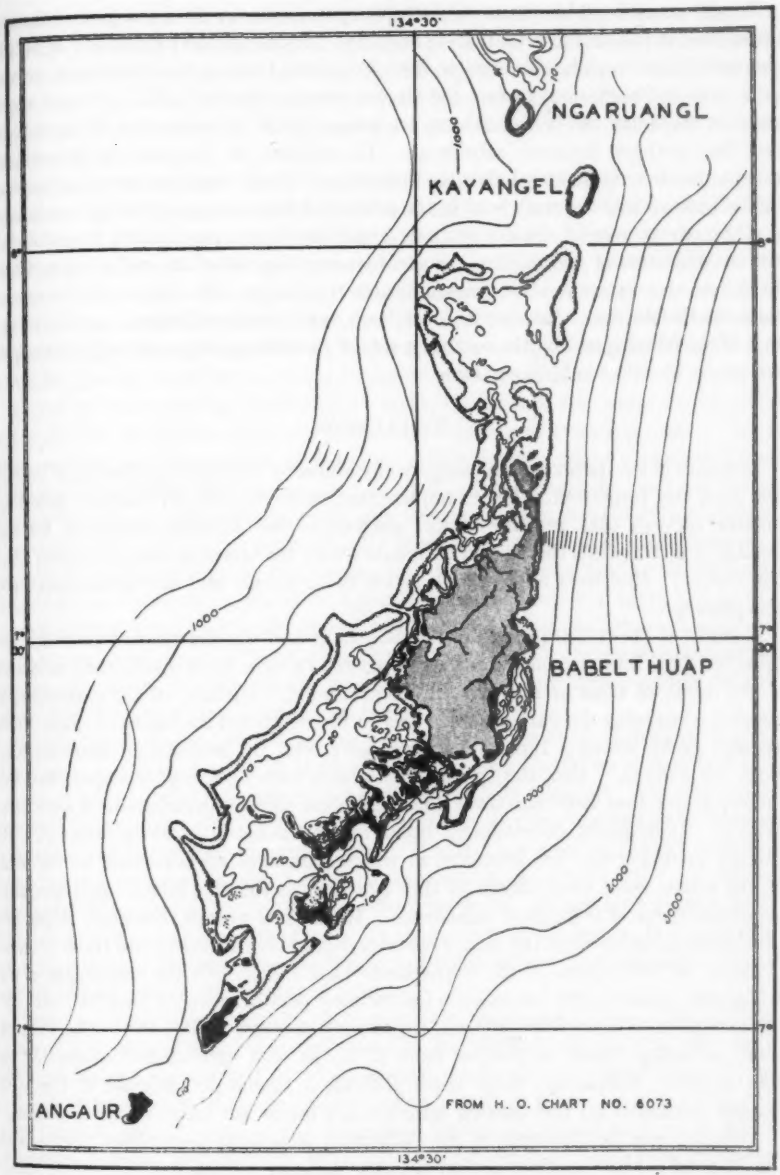


FIGURE 14.—*Palau Islands*

For 80 years there has been considerable speculation on the formation of the uplifted reefs of the southern islands of the group. Although the topography of Babelthuap indicates considerable erosion, there is nothing to prove that these reefs formed on a sinking foundation; in fact the stream terraces denote uplift. Several raised reefs on the south end of Babelthuap are located with the major axis down slope, a fact that perhaps disfavors subsidence. In addition, all the reefs on Babelthuap except one are considerably below the upland level which would permit erosion of the higher peaks while the reefs were in the process of formation on a rising foundation.

Although an area of obvious tectonic instability is not particularly favorable for the consideration of reef origins, the accordance of depths of the major lagoons and bank and the wave-cut shore lines indicates truncation with very little movement since the Pleistocene. Another factor difficult to explain by subsidence is the bifurcation of the fringing reef on the southeast side of Babelthuap when the off-shore slopes are nearly identical in both sections.

CONCLUSIONS

The data in this paper do not categorically affirm or condemn any theory of barrier and atoll reef formation. The examples cited, however, furnish evidence based on reliable surveys that permits critical analysis of the adjuncts necessary for the tenability of Darwin's theory and correlation with the tenets of Daly's Glacial Control theory. New data on reef and lagoon relationships and submarine slopes are also presented.

A study of about 200 profiles in the Marshalls and Carolines, some of which approached 2500 fathoms, indicates that slopes are variable to an extent that estimates of the depth of talus or reef growth are precluded. Further, no generalization is possible concerning the variation of slopes on the windward and leeward sides. The average profile shows a typical catenary curve with the anticipated diminution of slope with depth. Also, the smaller atolls have somewhat higher slopes than the larger, a fact that does not favor the theoretical talus accumulation of slow subsidence. In addition, no consistent break in slope is found at 40–50 fathoms. Although there are but few instances in which soundings are adequate to the level of the ocean floor, no evidence of ring synclines is found, perhaps an expectable accompaniment of individual subsidence. In the two groups, however, slopes are considerably higher than the older estimates, not much different from those Kuenen (1933, p. 95–100) found in the Netherlands East Indies. Of the seamounts in the stable area slopes to 500 fathoms are for the most part between 25° and 30°, with 35° not exceptional; below 1000 fathoms slopes may decrease to 10°–15°. The steepest slope, excluding Ngatik, is the east flank of Wotje, with some declivities over 50° to 400 fathoms. Obviously, these slopes indicate a significant decrease in the mass usually calculated for reef-bearing seamounts, a factor not unfavorable to stability.

Although reef development in the Gilberts is somewhat anomalous, the reefs of the Marshalls and Carolines are remarkably uniform. With few exceptions maximum widths, largest reef islands, greatest heights, and fewest passes are to windward. The overall narrowness and uniform average are indicative of youth and contem-

poraneity; they are difficult to reconcile with Davis' premise of Pleistocene existence. Although the larger atolls usually have deeper passes, no correlation is possible with lagoon depths. Since passes are found at all depths from shallow boat passes to those at the level of the lagoon floor, it is conjectural whether they are closed by lateral reef encroachment. In general flood-tide currents are less than 2 knots through these passes.

A review of the shapes of the 77 atolls and 35 banks does not confirm the theory of symmetry and subsidence. Under the subsidence postulate it would be difficult to contend that a very angular atoll such as Kwajalein had sunk less than an oval one the size of Nukuoro. This general angularity of atoll shapes, particularly on the leeward side, supports the suggestion that sediment may not readily accumulate at sea level about seamounts in the open ocean. Further, the paucity of coral causeways and piers is unfavorable to subsidence, as is the fact that small atolls and banks lie close to large units separated only by shallow saddles.

Except for several of the shallow small atolls, the inboard reef walls are steep, do not grade into the lagoon floor, and show little evidence of a detrital slope. Nor is there evidence of detrital drift to leeward. With the exceptions described lagoon floors are remarkably level, a fact that is against the antecedent platform theory because this degree of levelness can probably result only from deposition or planation. It is very doubtful that the floors of large atolls and banks would all be level as a result of organic aggradation, not to mention the difficulty of having all platforms aggraded to the same depth and none, apparently, in the process of aggradation. Of the 140 entries there is not one pass notch below the level of the lagoon floor, nor is there any evidence of an outboard delta, regardless of lagoon area/reef-length ratios, nor any indication of a Pleistocene drainage pattern in any lagoon—three definite possibilities if atolls existed throughout the glacial period.

An absolute denial of detrital inwash and deposition from coral reefs is illogical. The theory, however, that atolls of vastly different sizes should be of similar depths in various belts of wind and current velocities is basically unsound. (1) The lagoon area/reef length ratios of large atolls are so large that the detritus available becomes insignificant when compared to small atolls. This fact is even more forcibly apparent when applied to large banks. (2) It is unreasonable to expect that the detrital supply should be similar in the trade and doldrum belts. (3) If detritus were available to the extent supposed by Davis, its entrance into the lagoon in appreciable quantity is largely precluded by the height and width of reef islands and the general absence of passages on the windward sides.

There are several basic factors that invalidate the concept of detrital leveling. It is well known that reefs effectively break up the surface waves of the open ocean and that lagoons are marked by short choppy waves of small amplitude. It has also been demonstrated that the diameter of the trochoid through which water particles move is only $\frac{1}{2^{\frac{1}{8}}}$ that of the surface at depths equivalent to $\frac{1}{2}$ wave length (Sverdrup, Johnson and Fleming, 1942, p. 519) and less than $\frac{1}{5^{\frac{1}{600}}}$ at depths of one wave length (Bowditch, 1938, p. 267). Thus, wave action cannot be an effective agent of distribution or planation in the lagoon, particularly in the doldrum belt, or n the open sea at depths required for truncation without eustatic lowering. It is

also illogical that a current which streams from a windward to a leeward passage should set up eddy currents as effective throughout the lagoon as the main stream. Although the characteristics of deeper lagoon currents are little known, aerial observations at Kwajalein and Eniwetok show massive streams with no evidence of appreciable surface eddy currents.

Further, the cited examples show that detrital filling is of secondary importance. The efficacy of detrital inwash and filling is incompatible with the bank and lagoon relationships in the Gilberts; with the gently sloping floor of Aur and pass and current distribution of Eniwetok in the Marshalls; with the excessive depth of Ngatik and the anomalous "two-story" effect of Nukuoro; and with the uneven floors of Nomwin, Murilo, Oroluk, and Zohhoiiyoru. Also, the banks in the west-central Carolines largely deny any theory except truncation, as does the accordance of lagoon depths of the reef-encircled volcanic islands, a site where detrital inwash must, if ever, be dominant. Thus, the theoretical considerations confirmed by various examples from the three groups find the adjuncts of the subsidence theory untenable.

Although it is difficult to cite evidence that condemns the antecedent platform theory (Ladd and Hoffmeister, 1936, p. 91), there are several relationships that singly or as a whole are unfavorable to it. If Pleistocene truncation is denied, the accordance of depth, the absence of known flat-topped seamounts at all depths, the general paucity of coral heads in the deeper lagoons, the levelness of lagoon floors, and the presence of phosphate deposits in the centers of lagoonless coral islands are not easily explained.

Few definitive data can be contributed toward a solution of the difficult problem of stability. As far as known, Palau is the only volcanic island with considerably uplifted reef rock. This is of little significance, however, because the well-defined foredeep denotes a tectonically unstable region. The excessive depths of Ngatik and Nukuoro indicate subsidence. Yet neither of these atolls is normal; Ngatik's abnormal western flank slope and Nukuoro's irregular growth preclude generalization. The shallow lagoons and banks as well as the slightly uplifted coral islands in the Gilberts suggest emergence rather than subsidence. Angaur and Fais also indicate emergence.

The remaining 75 atolls, lagoons of the five reef-encircled islands, and the 35 banks are 50 fathoms deep or less, the range prescribed by the Glacial Control theory. Since detrital filling and leveling have been found deficient and aggradation improbable, truncation alone meets the various requirements without recourse to the special condition of long stillstand followed by uniform world-wide subsidence. It must, therefore, be concluded that stability was sufficient for complete truncation at a similar level. Since, however, truncation may have been in force until late Pleistocene time, the only factor that indicates stability for a long period is the absence of known banks below 50 fathoms. It is possible, although improbable, that subsequent hydrographic surveys may find submerged seamounts at all depths.

There is, however, one condition that Daly's theory fails to meet in the Marshalls and Carolines if absolute stability is demanded since Pleistocene. Although it has been assumed that detrital filling since the last period of truncation has been responsible for the decrease in depth of the smaller atolls, as shown in Figure 15 in which

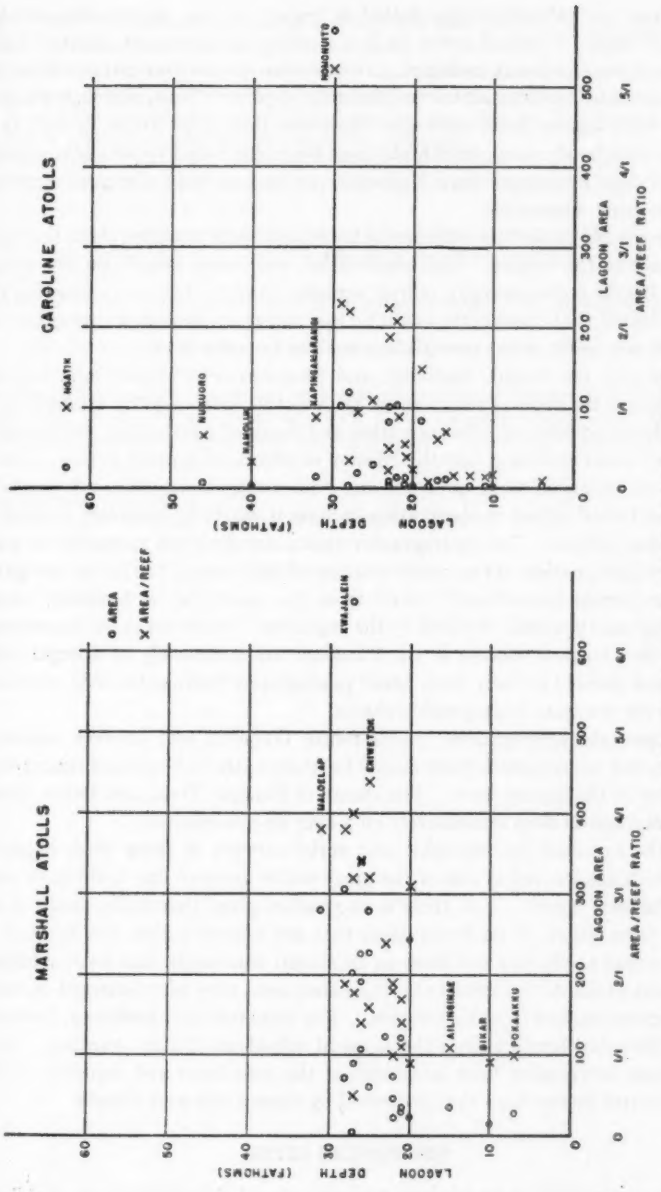


FIGURE 15.—*Graphs of the Marshall and Caroline atolls*

the Carolines and Marshalls are plotted in respect to size, lagoon area/reef-length ratios, and depth, a logical curve finds a number of discrepant points. Further, there is no evident regional variation, no correlation of pass/reef ratios, and no physical deviation that can account for the abnormal depths. Thus, although small atolls generally have lagoon floors somewhat shallower than large atolls, as well as more numerous coral heads, some seamounts must have either undergone slight subsidence and others slight emergence since Pleistocene, or various rates of organic aggradation must have been responsible.

Davis explicitly denied the presence of truncated spurs or cliffed shore lines on volcanic islands in the tropics. This observation was based largely on his voyage in the south Pacific and on a study of hydrographic charts. Daly, in answering Davis' criticism, stated that these cliffs would be low and quite probably covered by water or detritus as a result of the post-Pleistocene rise in ocean level.

Theoretically the height, declivity, and prominence of cliffs would depend on several factors: the state of reduction of the volcanic land mass by erosion; the condition of decomposition and disintegration as a result of weathering; the amount and duration of water lowering; and the efficacy of wave and current action. The first two, if in an advanced stage, preclude any bold, conspicuous cliffs, a fact that may account for Davis' failure in observation because it would be necessary in most cases to pass close inshore. Too, hydrographic charts are designed primarily for navigation, a fact that provides for accurate location of high points, the better navigational aids. The terrain immediately inland from the shore line is, however, relatively unimportant and is usually stylized by the engraver. As shown in the accompanying charts all five volcanic islands in the Carolines are moderately or abruptly cliffed, observations derived entirely from aerial photographs because no cliffs were detectable from the accurate hydrographic charts.

The large-scale hydrographic charts refute Davis in still another manner. If truncation had not occurred, there should be underwater indication of spurs plunging to the level of the lagoon floor. The charts of Ponape, Truk, and Palau, however, show the lagoons as deep immediately off a spur as a re-entrant.

Thus, the excellent hydrographic and aerial surveys of these three magnificent groups which are located in one of the great stable areas of the world have enabled a comprehensive report. Yet, there is no positive proof that atolls cannot form on subsiding foundations or on foundations that are formed within the depth of coral growth, or that atolls may not form on truncated seamounts that have subsided, or that present atolls do not crown the truncated coral caps of submerged seamounts, or that lagoons cannot form by solution. The demonstrated inefficacy, however, of detrital filling and leveling finds the classical subsidence theory wanting. In turn, it is difficult to visualize finer testament of the soundness and capacity of Daly's Glacial Control theory than that presented by these atolls and islands.

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OFFICIAL CALENDAR

Sept.	14–15	Meeting of Committee on Organization, Policies, and Administration
Sept.	15	Final date for submission of project applications for action in October
Oct.	1	Final date for filing Fellowship nominations for action 1946
Oct.	5	Meetings of Publications and Projects Committees
Oct.	15	Final date for submission of abstracts for Annual Meeting program
Oct.	19	Meeting of Program Committee for Annual Meeting
Oct.	25	Meetings of Budget, Finance, and Membership committees
Oct.	26	Council Meeting